RECEIPT # 63942
AMOUNT $ 250
SUMMONS ISSUED Y-2
LOCAL RULE 4.1
WAIVER FORM
MCF ISSUED
BY DPTY. CLK.
DATE 5-3-05

IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF MASSACHUSETTS

iROBOT CORPORATION, Plaintiff, v. URUS INDUSTRIAL CORPORATION, and KOOLATRON, a DIVISION of URUS INDUSTRIAL CORPORATION Defendants.	Civil Action No. 05 CV 10914

MAGISTRATE JUDGE Alexander

COMPLAINT

Plaintiff iROBOT CORPORATION, ("iRobot"), for its complaint against defendants URUS INDUSTRIAL CORPORATION and KOOLATRON (collectively "Defendants"), alleges as follows:

NATURE OF THE ACTION

1. In this action, iRobot seeks damages and a permanent injunction for infringement of its patent rights pursuant to Title 35 of the United States Code, infringement of its copyrights pursuant to Title 17 of the United States Code and for violations of the Lanham Act (Title 15 of the United States Code).

2. More particularly, this is an action, *inter alia*, for infringement of iRobot's patent, copyright and trade dress rights that iRobot secured through its successful efforts to develop and commercialize its well-known and commercially successful Roomba® Robotic Floorvac. Upon information and belief, Defendants have

been and still are directly infringing, contributorily infringing, or actively inducing infringement by others of one or more claims of iRobot's patents, infringing iRobot's copyrights and violating the Lanham Act, by making, using, selling and/or offering for sale, robotic vacuum products including the Koolvac, such as the Koolvac KV-1 model, and packaging and manuals that accompany Defendants' infringing products.

3. iRobot is the world leader in the development and marketing of household robotic floor vacuum cleaners, due in no small measure to its outstanding technical achievements and innovative industrial designs. iRobot's intellectual property is the result of its extensive and successful research and development programs.

4. On information and belief, in or about March 2005 Koolatron launched a robotic vacuum cleaner system called "Koolvac" which Koolatron markets as a "*SMART* Floor & Carpet Vacuum" that is easy to use.

5. On information and belief, Koolatron has directly sold and is continuing to sell Koolvac products through one or more internet websites including, without limitation, Koolatron.com, WonderfulBuys.com and YouCanSave.com. In addition, Koolatron has indirectly sold and is continuing to sell Koolvac through other internet websites including, without limitation, Amazon.com.

6. Defendants' Koolvac robotic vacuum cleaners are a studied and careful reproduction – a complete "knock-off" – of iRobot's successful Roomba® robotic vacuum cleaner. This appears to be an attempt by Koolatron to seize a significant part of iRobot's business by: infringing on iRobot's patented technology, impermissibly copying iRobot's copyrighted works and infringing on iRobot's trade dress.

iRobot brings this action, seeking both injunctive relief and damages. iRobot respectfully requests that this Court enjoin Koolatron from making, using, selling and offering for sale the robotic vacuum cleaners including the Koolvac robotic vacuum cleaners and further requests an award of damages to compensate it for the injuries it has already suffered. iRobot also requests that it be awarded treble damages, statutory damages, attorneys' fees, and related legal costs and expenses.

THE PARTIES

7. iRobot is a corporation organized and existing under the laws of the State of Delaware and having a principle place of business at 63 South Avenue, Burlington, Massachusetts 01803-4903.

8. Upon information and belief, Defendant Urus Industrial Corporation is a limited liability company organized and existing under the laws of Canada and having its principal place of business at 27 Catharine Avenue, Brantford, Ontario, Canada N3T 1X5A.

9. Upon information and belief, Defendant Koolatron is division of Urus Industrial Corporation and wholly owned by Urus Industrial Corporation, and through the Koolatron division Urus Industrial Corporation manufactures, markets, sells and imports the robotic vacuum systems that are the subject matter of this action. Koolatron was a distributor of iRobot's Roomba® robotic vacuum cleaner product from March 2003 until May 2004.

10. Upon information and belief, Koolatron makes, uses, sells and/or offers for sale throughout the United States robotic vacuum cleaners alleged herein to infringe one or more claims of at least one of iRobot's United States Patent

Nos. 6,594,844; 6,809,490; and 6,883,201. Upon information and belief, Koolatron does business in this Judicial District.

JURISDICTION AND VENUE

11. This action for patent infringement arises under the Patent Laws of the United States, 35 U.S.C. § 1 *et seq*. Jurisdiction and venue are based on 28 U.S.C. §§ 1331, 1338, 1391(b), 1391(c) and/or 1400(b).

FIRST CAUSE OF ACTION
(For Patent Infringement)

12. iRobot repeats and realleges the allegations of paragraphs 1 through 11 above.

13. On July 22, 2003, U.S. Patent No. 6,594,844 ("the '844 patent"), entitled "Robot Obstacle Detection System," was duly and legally issued to Joseph L. Jones. The entire right, title and interest in and to the '844 patent, including the right to sue and recover for any and all past infringement thereof, is assigned to iRobot. A true and correct copy of the '844 patent is attached hereto as Exhibit 1.

14. Upon information and belief, Defendants have been and are now directly infringing, contributorily infringing, and/or actively inducing infringement by others of one or more claims of the '844 patent by making, using, selling, and/or offering to sell, and/or actively inducing others to make, use, sell, and/or offer to sell, in this Judicial District and elsewhere, products covered by one or more claims of the '844 patent, including products designated as the Koolvac robotic vacuum cleaners.

15. Upon information and belief, Defendants' infringement and active inducement of infringement has been willful and deliberate, rendering this case "exceptional" within the meaning of 35 U.S.C. § 285.

16. iRobot has been damaged and will be irreparably injured by Defendants' continuing infringement and active inducement of infringement, for which iRobot has no adequate remedy at law. Defendants' infringing activities will continue unless enjoined by this Court.

SECOND CAUSE OF ACTION
(For Patent Infringement)

17. iRobot repeats and realleges the allegations of paragraphs 1 through 11 above.

18. On October 26, 2004, U.S. Patent No. 6,809,490 ("the '490 patent"), entitled "Method and System for Multi-mode Coverage for an Autonomous Robot," was duly and legally issued to Joseph L. Jones and Phillip R. Mass. The entire right, title and interest in and to the '490 patent, including the right to sue and recover for any and all past infringement thereof, is assigned to iRobot. A true and correct copy of the '490 patent is attached hereto as Exhibit 2.

19. Upon information and belief, Defendants have been and are now directly infringing, contributorily infringing, or actively inducing infringement by others of one or more claims of the '490 patent by making, using, selling, and/or offering to sell, and/or actively inducing others to make, use, sell, and/or offer to sell, in this Judicial District and elsewhere, products covered by one or more claims of the '490 patent, including products designated as the Koolvac robotic vacuum cleaners.

20. Upon information and belief, Defendants' infringement and active inducement of infringement have been willful and deliberate, rendering this case "exceptional" within the meaning of 35 U.S.C. § 285.

21. iRobot has been damaged and will be irreparably injured by Defendants' continuing infringement and active inducement of infringement, for which iRobot has no adequate remedy at law. Defendants' infringing activities will continue unless enjoined by this Court.

THIRD CAUSE OF ACTION
(For Patent Infringement)

22. iRobot repeats and reallege the allegations of paragraphs 1 through 11 above.

23. On April 26, 2005, U.S. Patent No. 6,883,201 ("the '201 patent"), entitled "Autonomous Floor-Cleaning Robot," was duly and legally issued to Joseph L. Jones, Newton E. Mack, David M. Nugent and Paul E. Sandin. The entire right, title and interest in and to the '201 patent, including the right to sue and recover for any and all past infringement thereof, is assigned to iRobot. A true and correct copy of the '201 patent is attached hereto as Exhibit 3.

24. Upon information and belief, Defendants have been and are now directly infringing, contributorily infringing and/or actively inducing infringement by others of one or more claims of the '201 patent by making, using, selling, and/or offering to sell, and/or actively inducing others to make, use, sell, and/or offer to sell, in this Judicial District and elsewhere, products covered by one or more claims of the '201 patent, including products designated as the Koolvac robotic vacuum cleaners.

25. Upon information and belief, Defendants' infringement and active inducement of infringement have been willful and deliberate, rendering this case "exceptional" within the meaning of 35 U.S.C. § 285.

FOURTH CAUSE OF ACTION
(For Copyright Infringement)

26. iRobot repeats and realleges the allegations of paragraphs 1 through 11 above.

27. This is a claim for infringement of the copyrights in iRobot's product literature, and system interface, including its musical audio feedback features, arising under the U.S. Copyright Act, 17 U.S.C. § 101 *et seq.*

28. By the foregoing acts, Defendants have infringed iRobot's copyrights and have created, displayed and distributed, and contributed to the creation, display and distribution of unauthorized derivative works.

29. Upon information and belief, Defendants' copying of and creation of derivative works based on the Roomba® robotic floorvac and its product literature has been willful and with knowledge of iRobot's copyrights, and has resulted in damage to iRobot.

30. Upon information and belief, unless restrained by the Court, Defendants will continue to infringe iRobot's copyrights causing irreparable injury and damage to iRobot. iRobot has no adequate remedy at law.

FIFTH CAUSE OF ACTION
(For Trade Dress Infringement and False Designation of Origin in Violation of §43(a) of the Lanham Act)

31. iRobot repeats and realleges the allegations of paragraphs 1 through 11 above.

32. This is a claim for trade dress infringement and false designation of origin arising under Section 43(a) of the Lanham Act, 15 U.S.C. § 1125(a).

33. iRobot's Roomba® robotic floorvac has broad customer recognition in the United States and abroad. Moreover, these well-known robotic floorvacs have garnered numerous awards and press coverage thereby increasing the public goodwill in the trade dress and the products that they represent.

34. Defendants' activities, as alleged, constitute infringement and/or contributory infringement of iRobot's trade dress elements as manifested by the physical appearance of the Koolatron systems, as well as false designation of origin, false representation and false description, all to the substantial and irreparable injury of the public and of iRobot's business reputation and goodwill.

35. By such wrongful acts, Defendants have caused and, unless restrained by the Court, will continue to cause serious irreparable injury and damage to iRobot and to the goodwill associated with iRobot's trade dress, including diversion of customers from iRobot, lost sales and lost profits, and Defendants will be unjustly enriched. iRobot has no adequate remedy at law.

PRAYER FOR RELIEF

WHEREFORE iRobot demands judgment as follows:

(a) For judgment to be entered that Defendants have infringed the '844 patent;

(b) Finding that Defendants' infringement of the '844 patent has been willful and deliberate;

(c) Permanently enjoining Defendants, their officers, agents, all parent, subsidiary and affiliate corporations and other business entities, and all other persons or entities acting in concert, participation or in privity with them, and their

successors and assigns from further acts of infringement, contributory infringement or inducement of infringement of the '844 patent;

(d) For judgment to be entered that Defendants have infringed the '490 patent;

(e) Finding that Defendants' infringement of the '490 patent has been willful and deliberate;

(f) Permanently enjoining and restraining Defendants, their officers, agents, all parent, subsidiary and affiliate corporations and other business entities, and all other persons or entities acting in concert, participation or in privity with them, and their successors and assigns from further acts of infringement, contributory infringement or inducement of infringement of the '490 patent;

(g) For judgment to be entered that Defendants have infringed the '201 patent;

(h) Finding that Defendants' infringement of the '201 patent has been willful and deliberate;

(i) Permanently enjoining and restraining Defendants, their officers, agents, all parent, subsidiary and affiliate corporations and other business entities, and all other persons or entities acting in concert, participation or in privity with them, and their successors and assigns from further acts of infringement, contributory infringement or inducement of infringement of the '201 patent;

(j) For a judgment that Defendants' accused products and product literature infringe iRobot's copyrights and that Defendants' use and distribution of the accused product constitutes direct and contributory infringement of iRobot's copyrights;

(k) For a judgment that Defendants' accused products infringe iRobot's trade dress and that Defendants' use and distribution of the accused products constitute direct and contributory infringement of iRobot's trade dress;

(l) Awarding iRobot monetary damages, in an amount to be determined at trial, together with interest and costs as fixed by the Court;

(m) Awarding iRobot enhanced damages under 35 U.S.C. § 284;

(n) Awarding iRobot their reasonable attorneys' and experts' fees and their costs and disbursements in this action, as provided by 35 U.S.C. § 285;

(o) That Defendants be required to account to iRobot for Defendants' profits and the actual damages suffered by iRobot as a result of Defendants' acts of direct and contributory infringement, false designation of origin and unfair competition together with interest, that iRobot's recoveries be enhanced and/or trebled, and that prejudgment interest be awarded, pursuant to Sections 35 and 43 of the Lanham Act, 15 U.S.C. §§ 1117 and 1125; and

(p) Granting iRobot such other and further relief as is just and proper.

iRobot Corporation

By its attorneys,

Edward J. Kelly (BBO # 564529)
ROPES & GRAY LLP
One International Place
Boston, MA 02110-2624
(617) 951-7000

Attorneys for Plaintiff

Dated: May 3, 2005

US006594844B2

(12) **United States Patent**
Jones

(10) **Patent No.:** **US 6,594,844 B2**
(45) **Date of Patent:** **Jul. 22, 2003**

(54) **ROBOT OBSTACLE DETECTION SYSTEM**

(75) Inventor: **Joseph L. Jones**, Acton, MA (US)

(73) Assignee: **iRobot Corporation**, Burlington, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 220 days.

(21) Appl. No.: **09/768,773**

(22) Filed: **Jan. 24, 2001**

(65) **Prior Publication Data**

US 2002/0016649 A1 Feb. 7, 2002

Related U.S. Application Data

(60) Provisional application No. 60/177,703, filed on Jan. 24, 2000.

(51) **Int. Cl.**^{7} **A47L 5/00**; A47L 9/28; A47L 11/00

(52) **U.S. Cl.** **15/49.1**; 15/319; 250/559.33; 901/47

(58) **Field of Search** 15/49.1, 50.1–50.3, 15/52.1, 98, 319, 340.1, 340.3, 340.4; 250/559.31, 559.33; 102/213; 901/47

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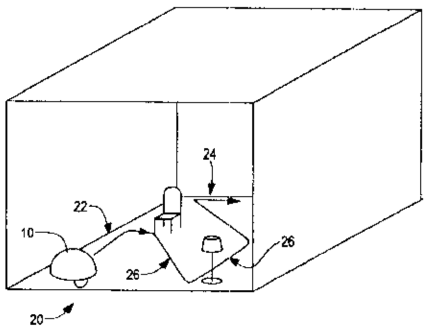
* cited by examiner

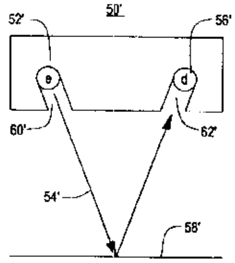
Primary Examiner—Terrence R. Till
(74) *Attorney, Agent, or Firm*—Iandiorio & Teska

(57) **ABSTRACT**

A robot obstacle detection system including a robot housing which navigates with respect to a surface and a sensor subsystem having a defined relationship with respect to the housing and aimed at the surface for detecting the surface. The sensor subsystem includes an optical emitter which emits a directed beam having a defined field of emission and a photon detector having a defined field of view which intersects the field of emission of the emitter at a region. A circuit in communication with a detector redirects the robot when the surface does not occupy the region to avoid obstacles. A similar system is employed to detect walls.

20 Claims, 19 Drawing Sheets





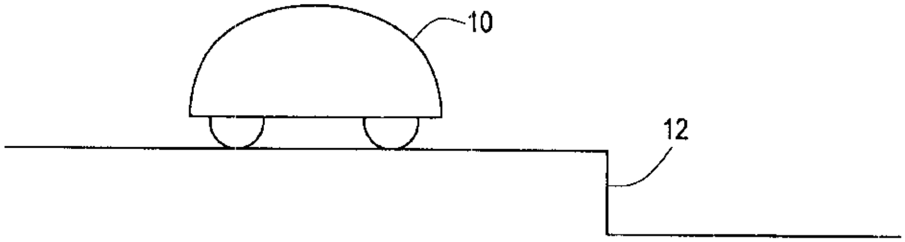


FIG. 1

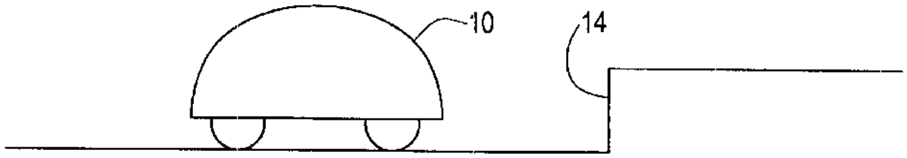


FIG. 2

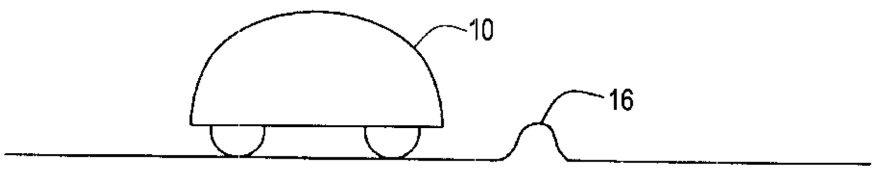


FIG. 3

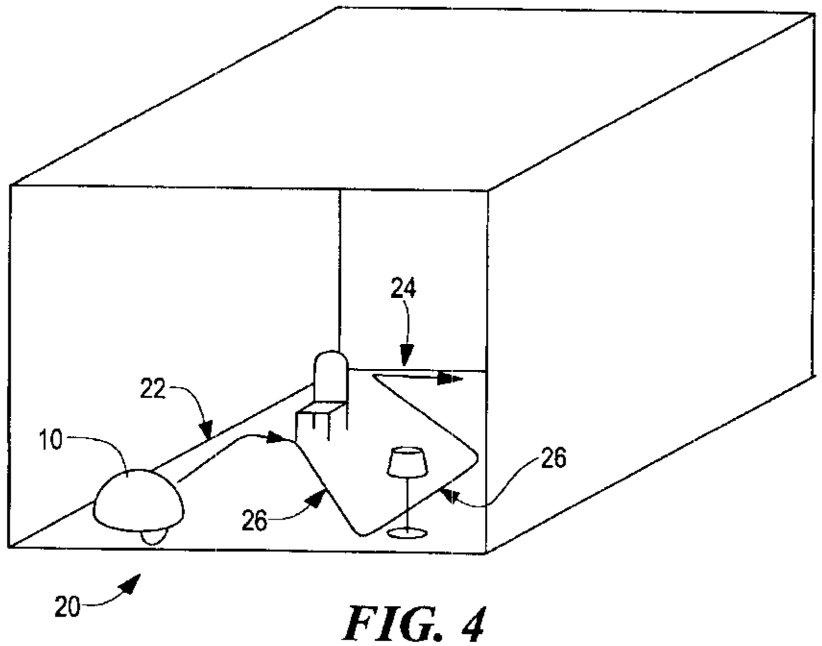


FIG. 4

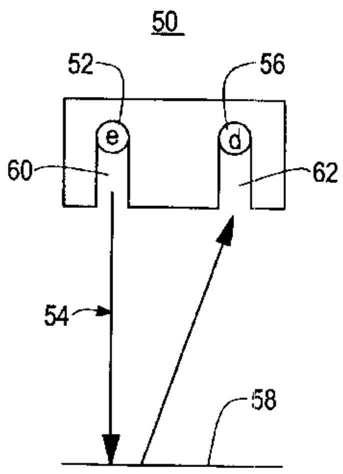


FIG. 5

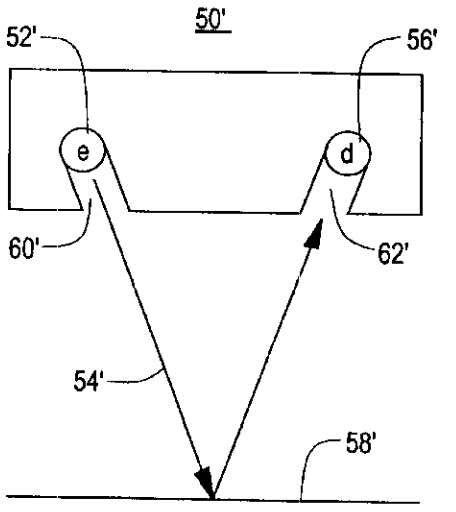


FIG. 6

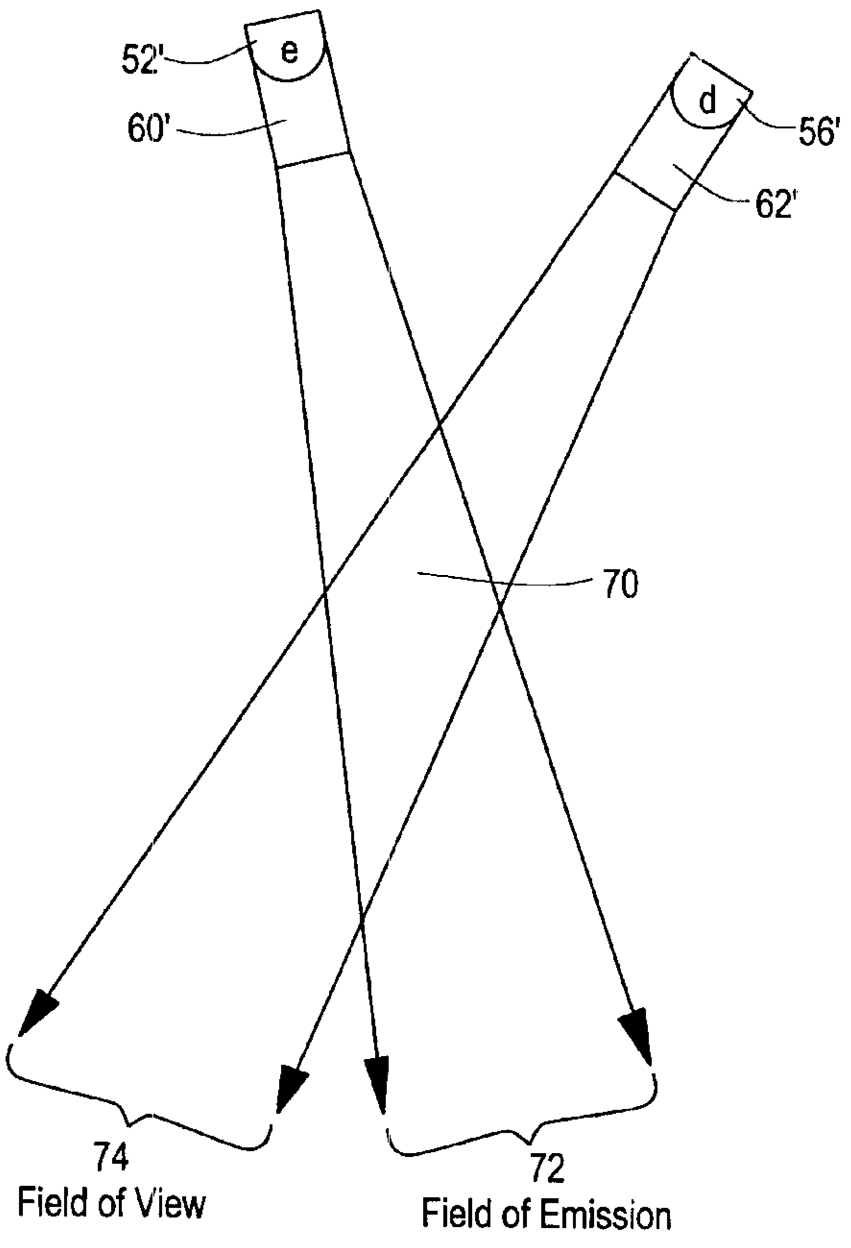


FIG. 7

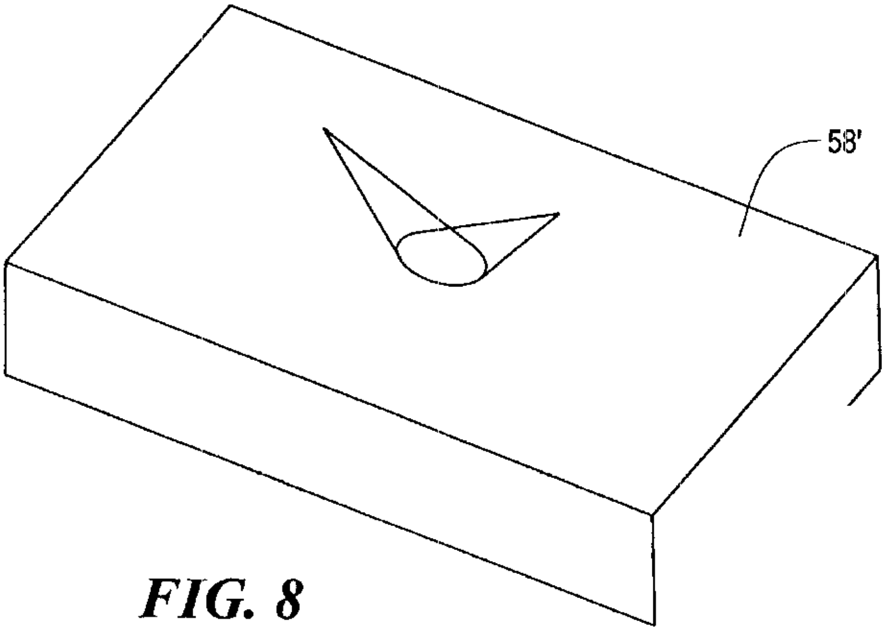


FIG. 8

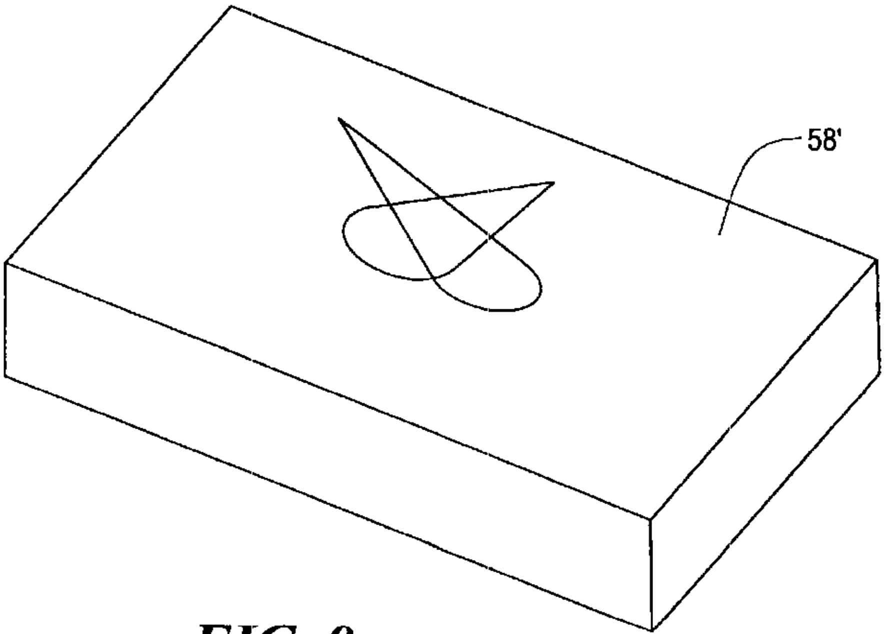


FIG. 9

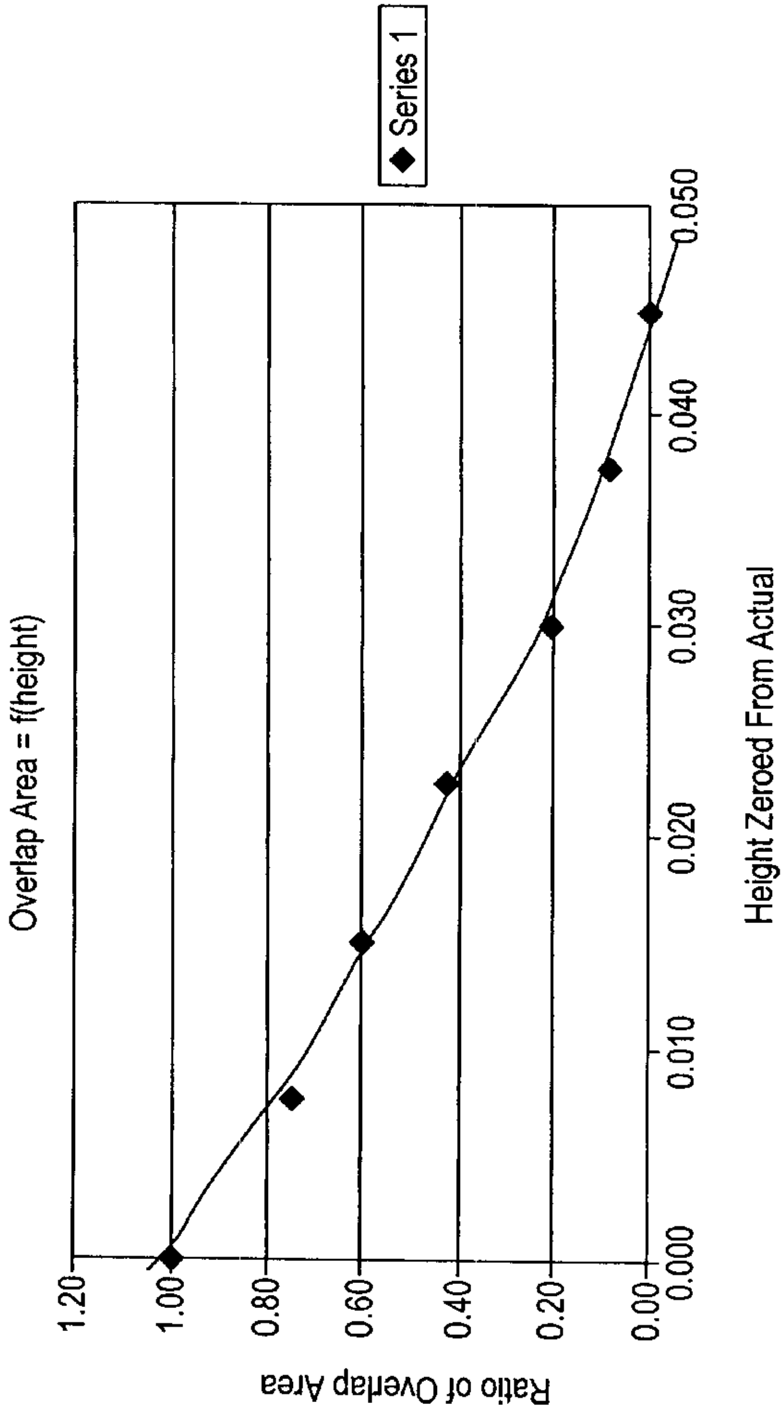
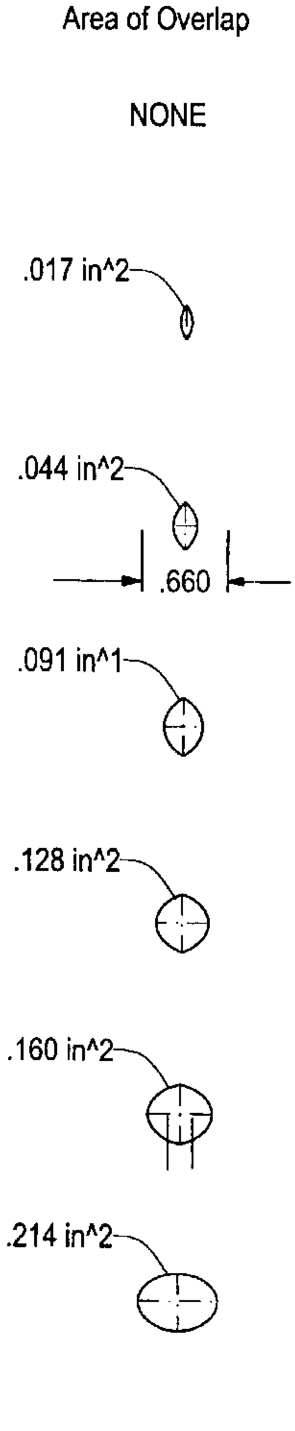
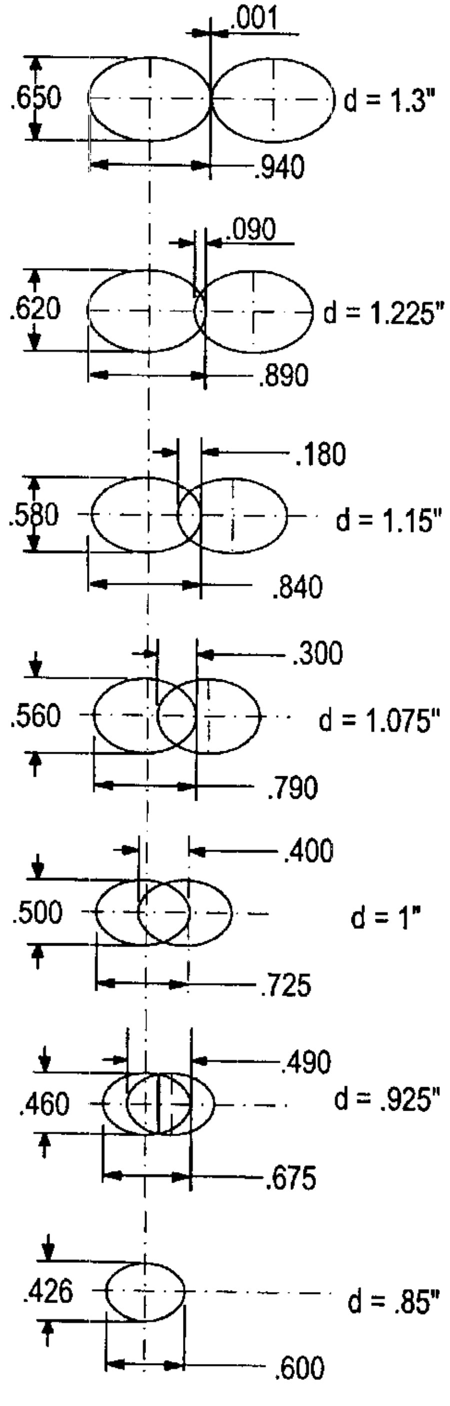

Overlap Area = f(height)
Series 1
Ratio of Overlap Area
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.000
0.010
0.020
0.030
0.040
0.050
Height Zeroed From Actual

FIG.10



Area of Overlap
NONE
.017 in^2
.044 in^2
.660
.091 in^1
.128 in^2
.160 in^2
.214 in^2

FIG. 12



.001
.650
d = 1.3"
.940
.090
.620
d = 1.225"
.890
.180
.580
d = 1.15"
.840
.300
.560
d = 1.075"
.790
.400
.500
d = 1"
.725
.490
.460
d = .925"
.675
.426
d = .85"
.600

FIG. 11

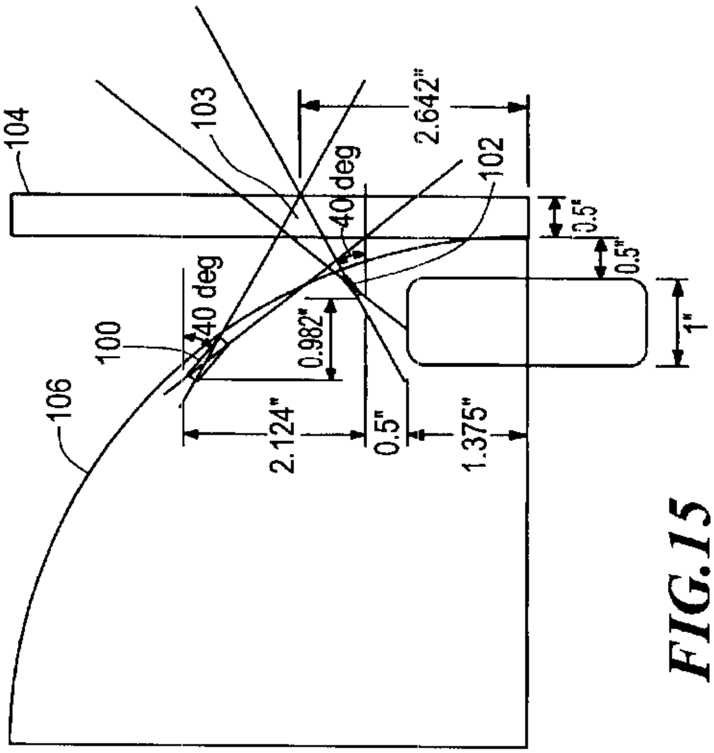

104
103
2.642"
102
40 deg
0.5"
0.5"
1"
40 deg
100
0.982"
106
2.124"
0.5"
1.375"

FIG.15

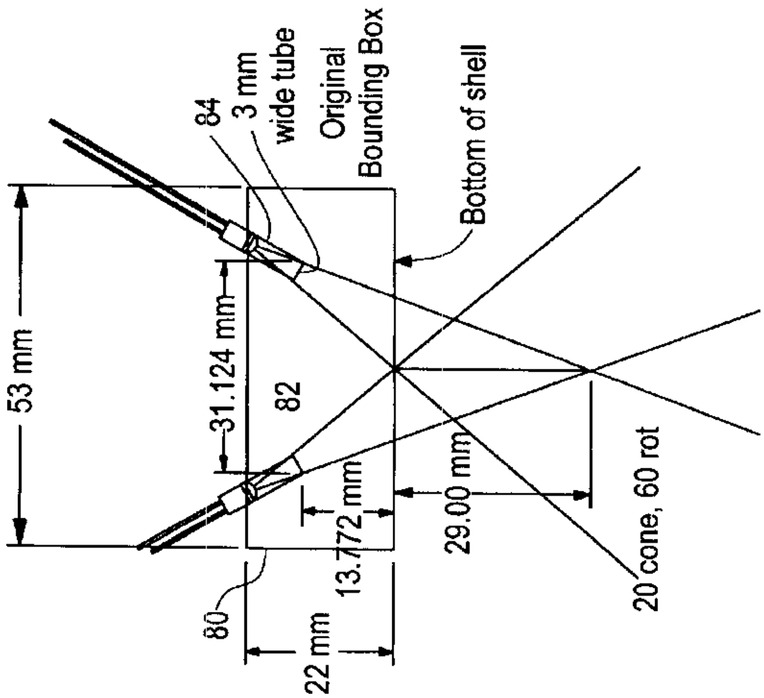

84
3 mm
wide tube
Original
Bounding Box
Bottom of shell
53 mm
31.124 mm
82
13.772 mm
29.00 mm
20 cone, 60 rot
80
22 mm

FIG. 13

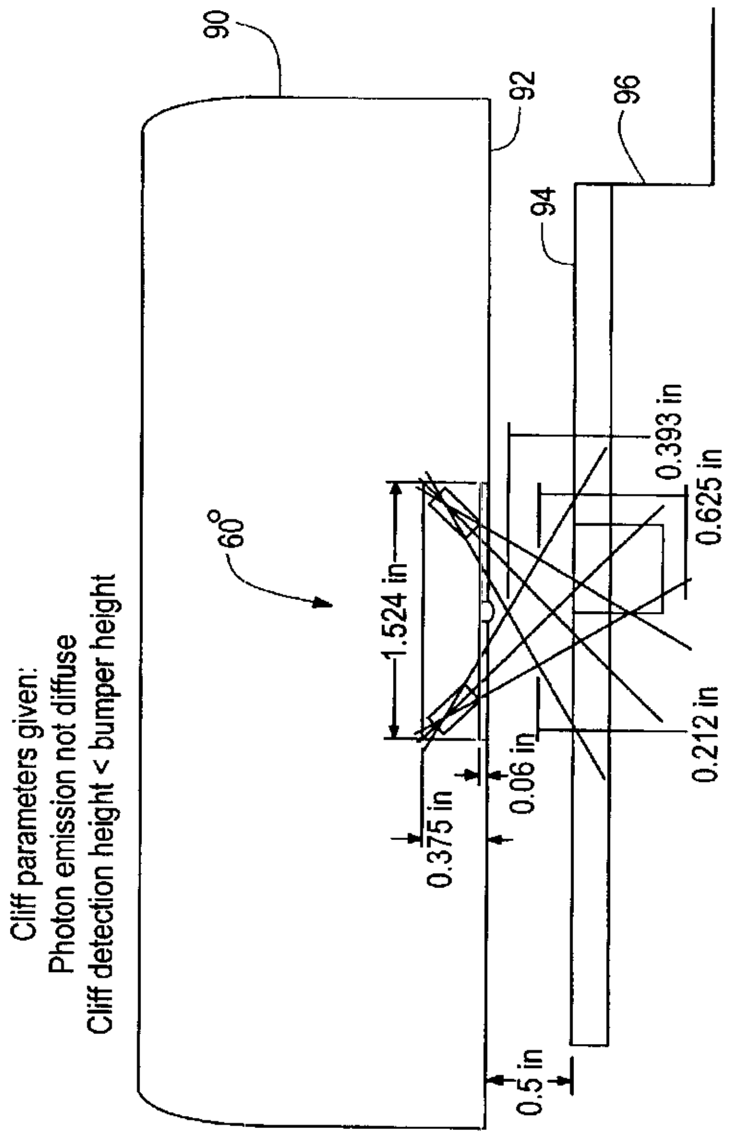

90
92
94
96
60°
Cliff parameters given:
Photon emission not diffuse
Cliff detection height < bumper height
1.524 in
0.375 in
0.06 in
0.393 in
0.625 in
0.212 in
0.5 in

FIG. 14

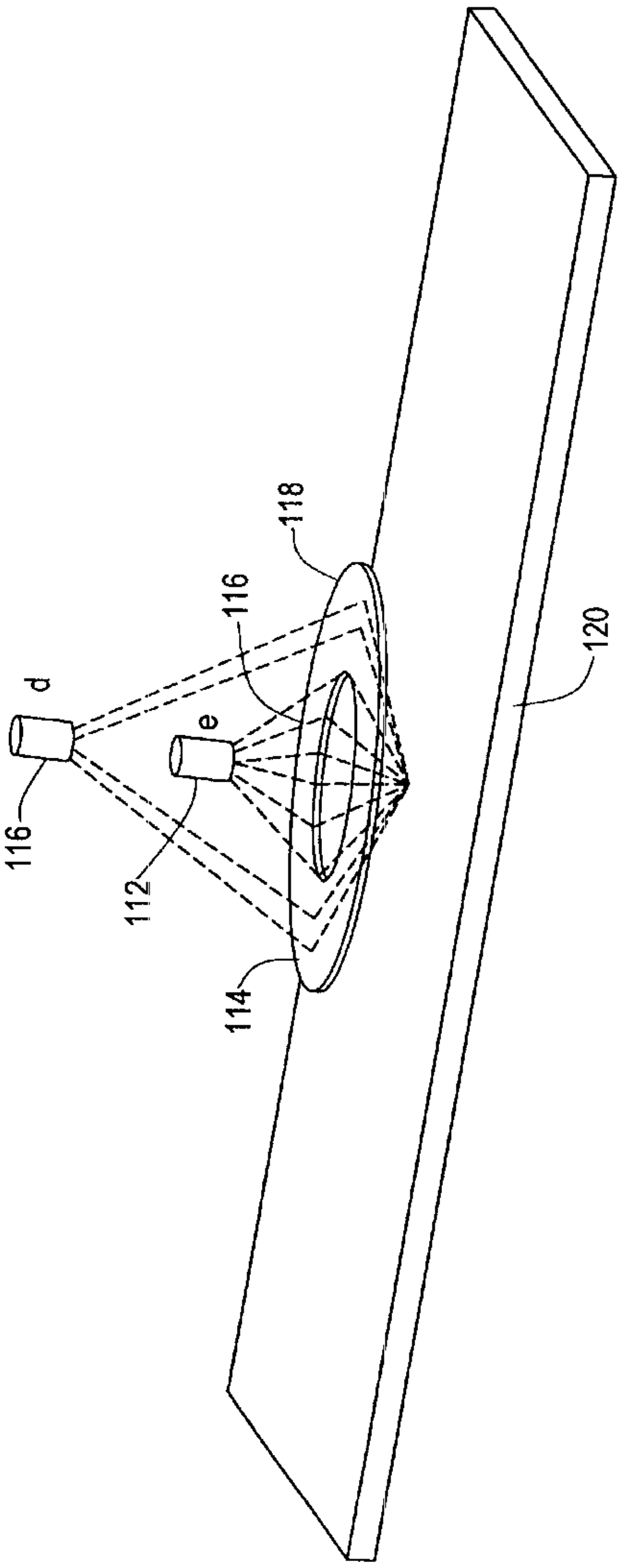


FIG.16

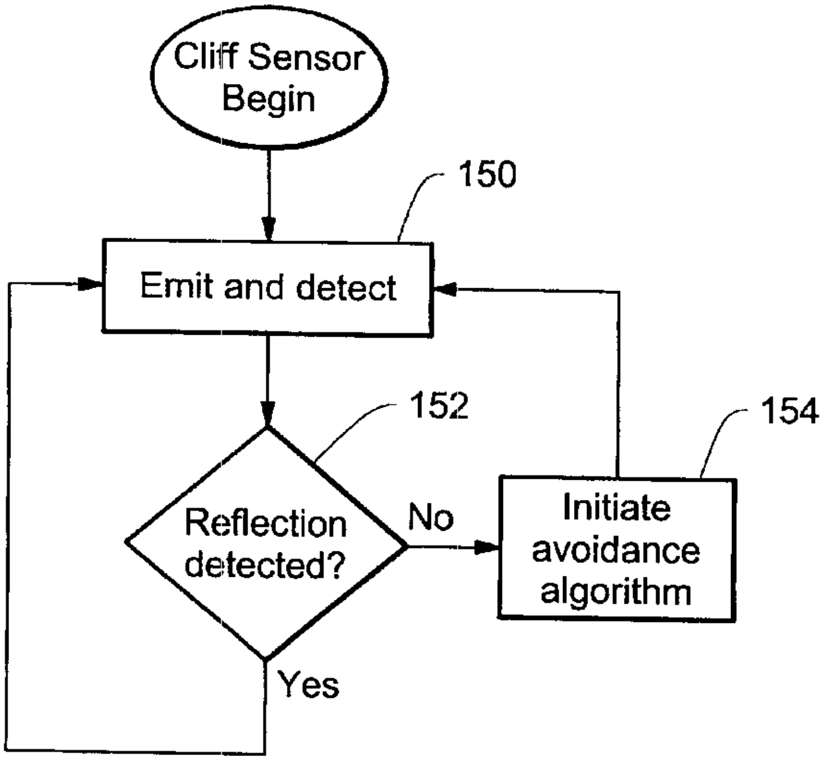

Cliff Sensor Begin
150
Emit and detect
152
154
Reflection detected?
No
Initiate avoidance algorithm
Yes

FIG. 17

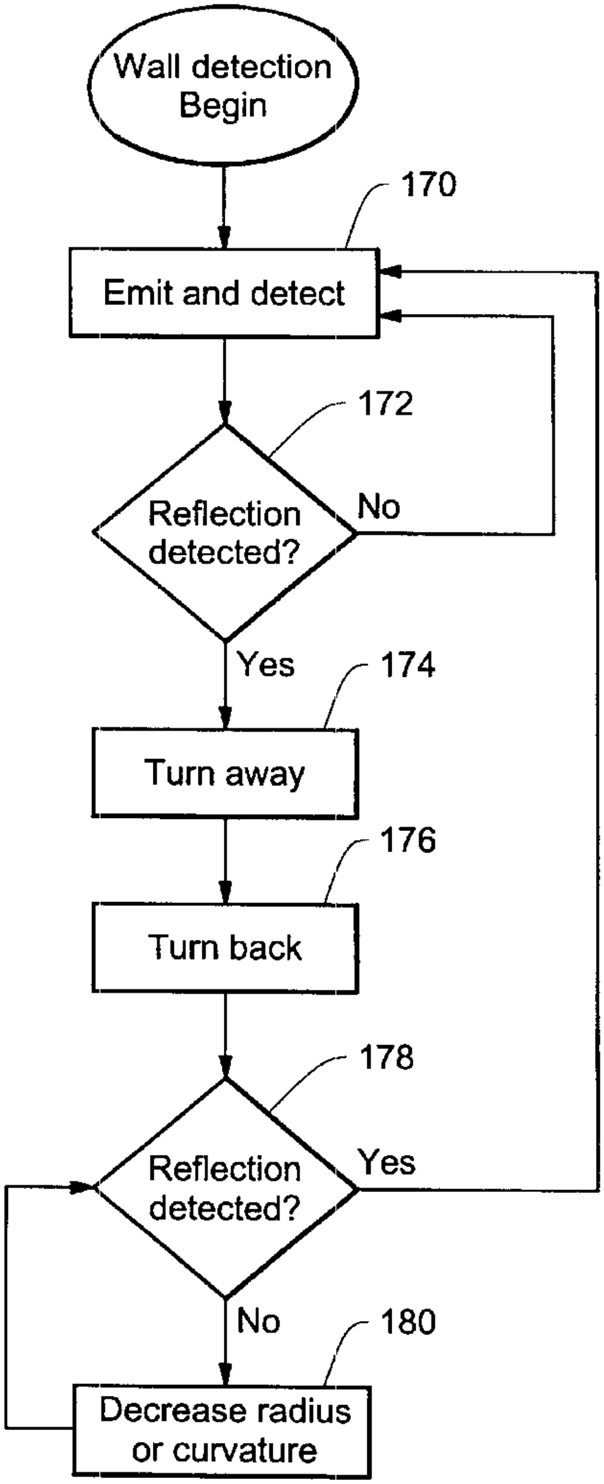

Wall detection
Begin
170
Emit and detect
172
Reflection
detected?
No
Yes
174
Turn away
176
Turn back
178
Reflection
detected?
Yes
No
180
Decrease radius
or curvature

FIG. 18

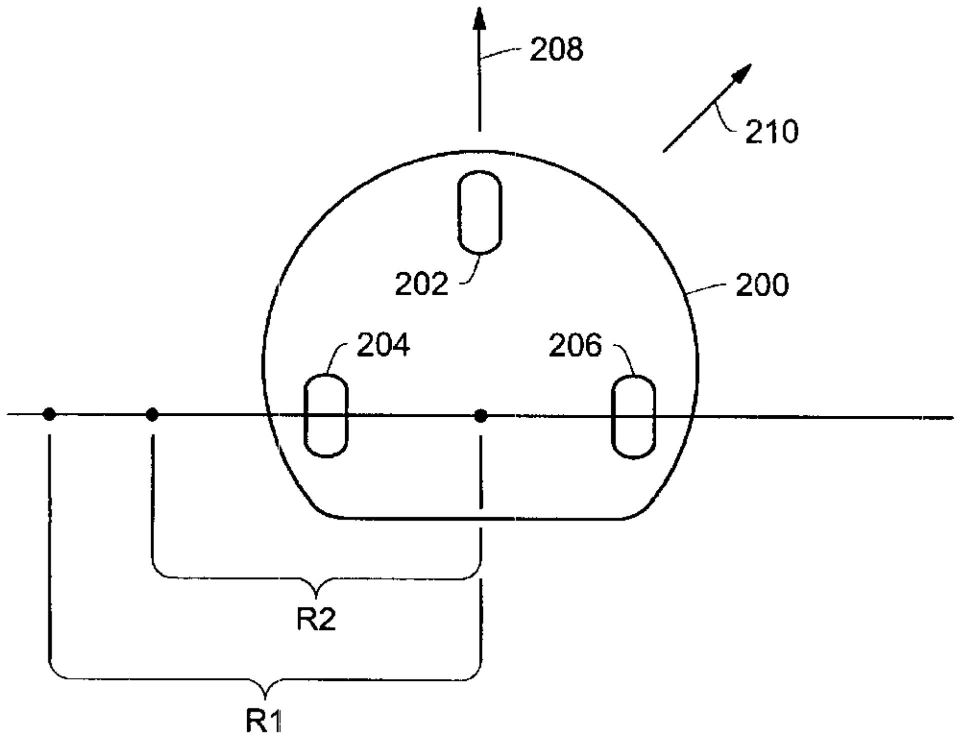


FIG. 19

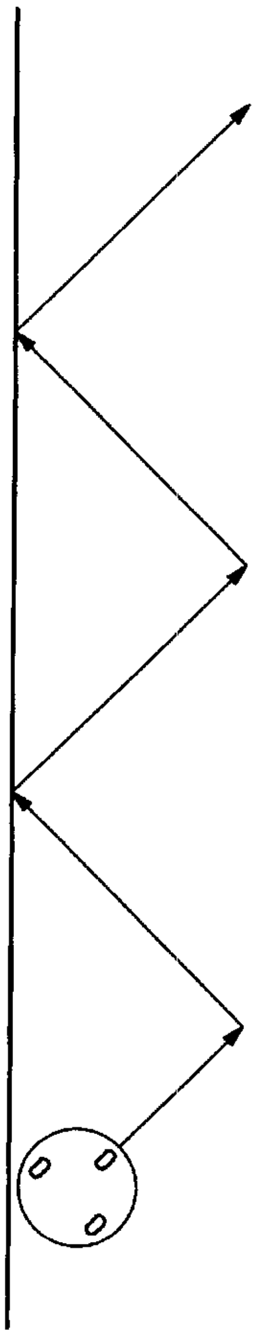


FIG. 20

FIG. 21

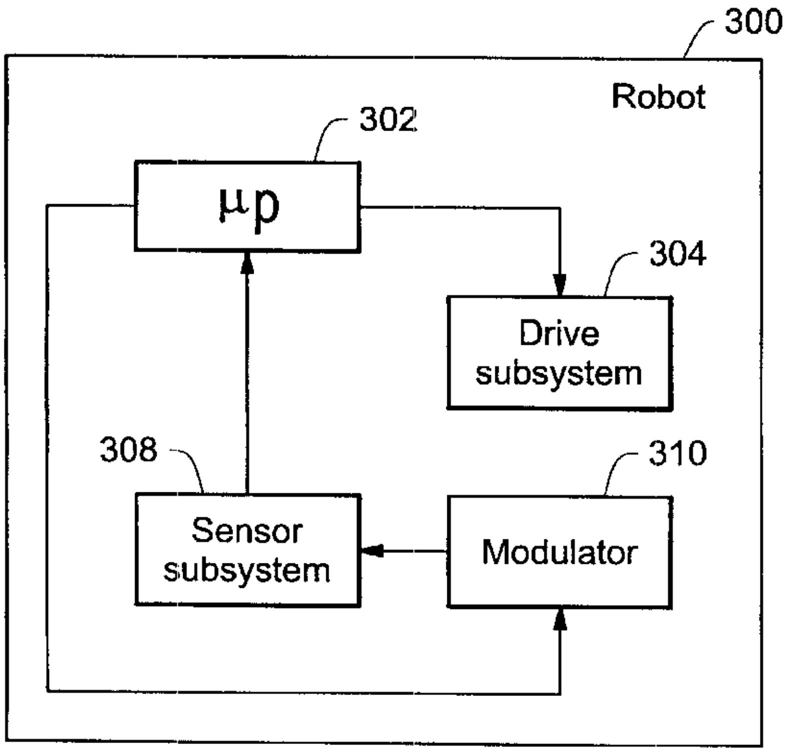

300
Robot
302
μp
304
Drive subsystem
308
310
Sensor subsystem
Modulator

FIG. 22

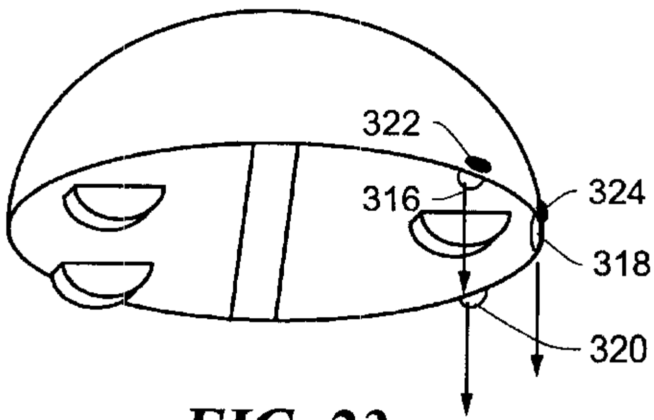

322
316
324
318
320

FIG. 23

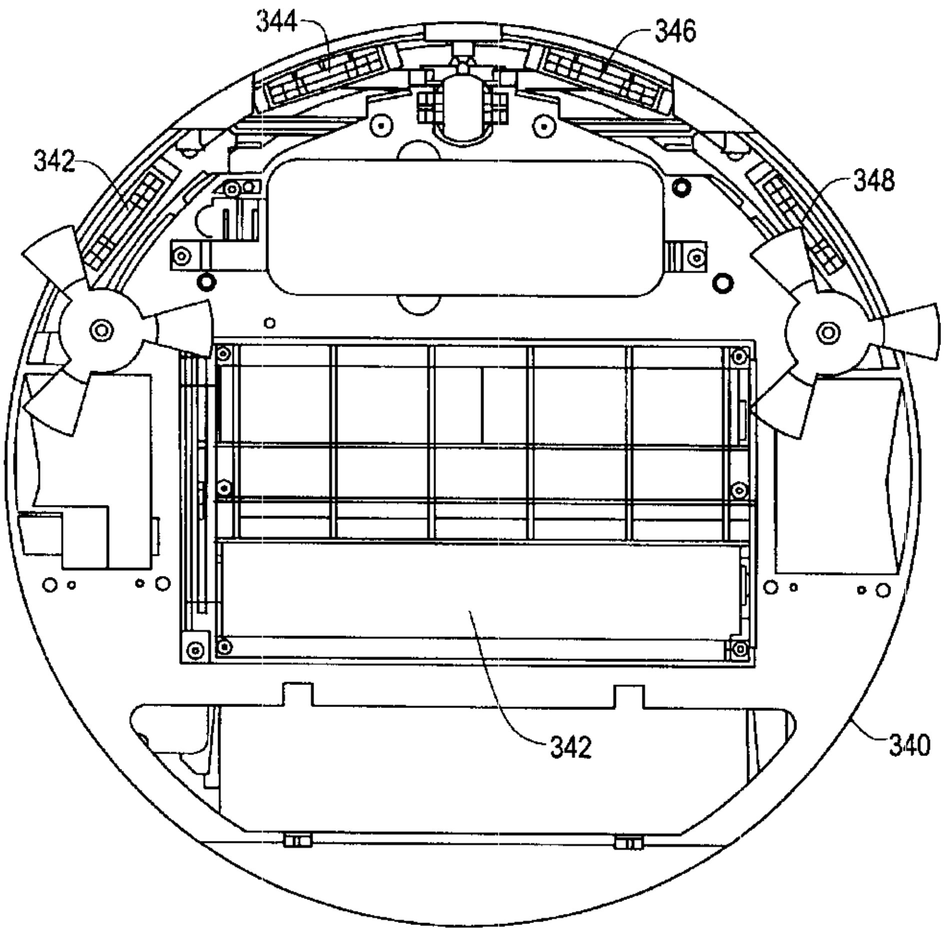


FIG. 24

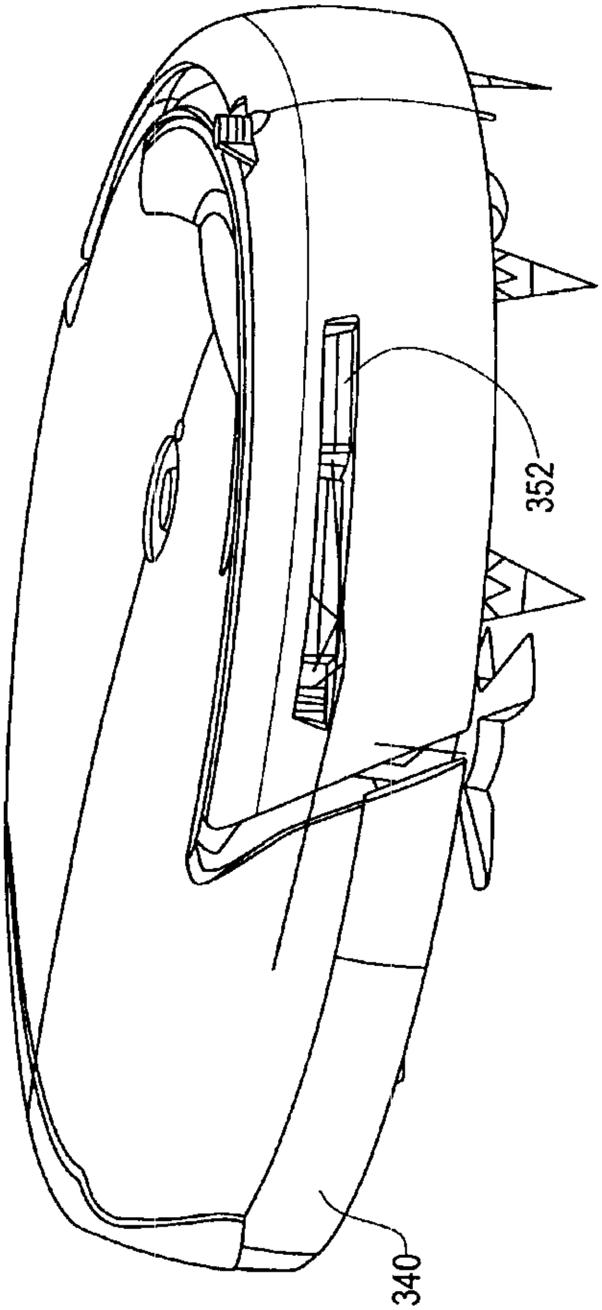


FIG.25

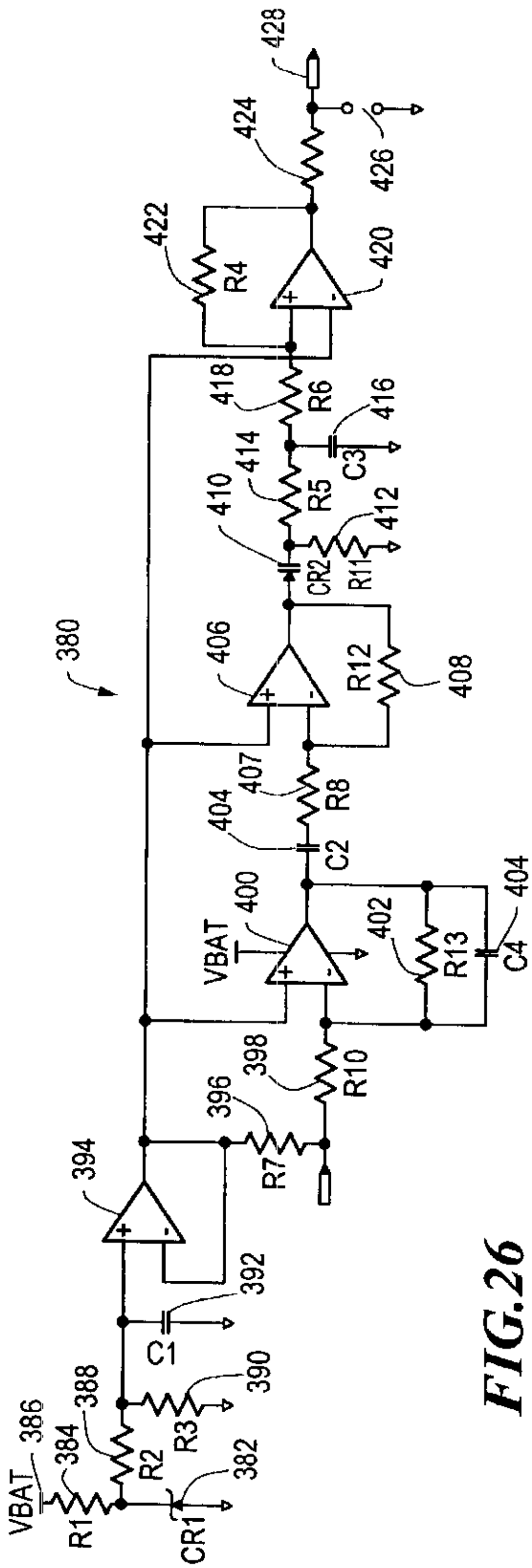

380
VBAT
386
384
388
R1
R2
R3
390
CR1
382
C1
392
394
396
R7
398
R10
VBAT
400
402
R13
C4
404
C2
404
407
R8
406
R12
408
CR2
410
R11
412
R5
414
C3
416
R6
418
420
R4
422
424
426
428

FIG.26

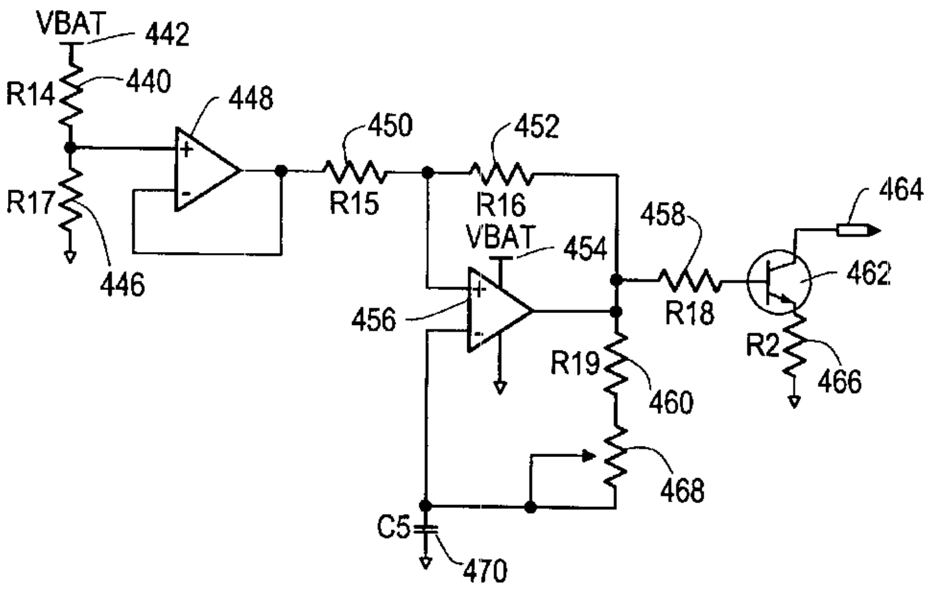

VBAT
442
R14
440
448
450
452
R17
R15
R16
VBAT
454
458
464
462
446
456
R18
R19
R2
466
460
468
C5
470

FIG. 27

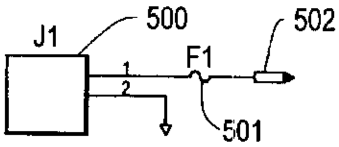


FIG. 28

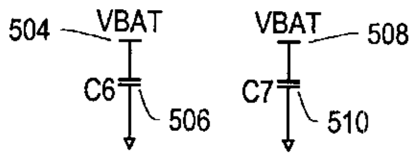


FIG. 29

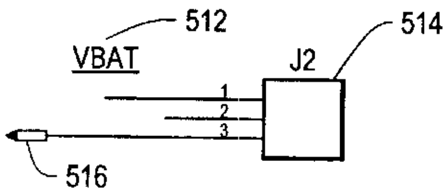


FIG. 30

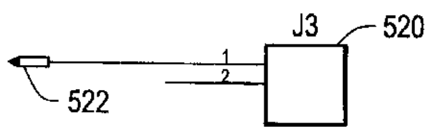


FIG. 31

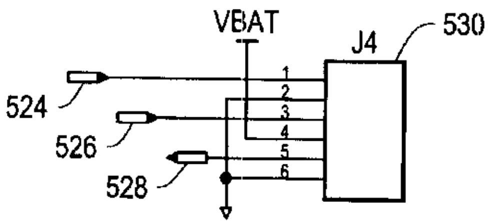


FIG. 32

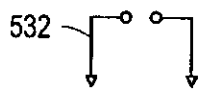


FIG. 33

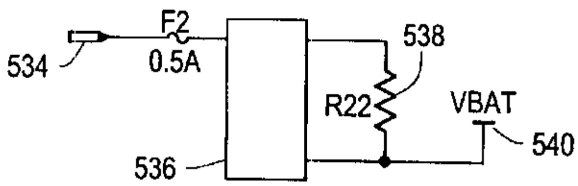


FIG. 34

ROBOT OBSTACLE DETECTION SYSTEM

PRIORITY CLAIM

This invention claims priority from Provisional Application Ser. No. 60/177,703 filed Jan. 24, 2000.

FIELD OF THE INVENTION

This invention relates to an obstacle detection system for an autonomous cleaning robot.

BACKGROUND OF THE INVENTION

There is a long felt need for autonomous robotic cleaning devices for dusting, mopping, vacuuming, and sweeping operations. Although technology exists for complex robots which can, to some extent, "see" and "feel" their surroundings, the complexity, expense and power requirements associated with these types of robotic subsystems render them unsuitable for the consumer marketplace.

The assignee of the subject application has devised a less expensive, battery operated, autonomous cleaning robot which operates in two modes: random and wall following. In the random bounce mode, the processing circuitry of the robot causes it to move in a straight line until the robot comes into contact with an obstacle; the robot then turns away from the obstacle and heads in a random direction. In the wall following mode, the robot encounters a wall, follows it for a time, and then returns to the random mode. By using this combination of modes, robotic theory has proven that the floor including the edges thereof is adequately covered in an optimal time resulting in a power savings.

Unfortunately, however, presently available sensor subsystems such as sonar sensors for detecting obstacles on or in the floor or for detecting the wall in order to enter the wall following mode (or to avoid bumping into the wall) are either too complex or too expensive of both. Tactile sensors are inefficient.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide a robot obstacle detection system which is simple in design, low cost, accurate, easy to implement, and easy to calibrate.

It is a further object of this invention to provide such a robot detection system which prevents an autonomous cleaning robot from driving off a stair or over an obstacle which is too high or too low.

It is a further object of this invention to provide a robotic wall detection system which is low cost, accurate, easy to implement and easy to calibrate.

It is a further object of this invention to provide such a robot wall detection system which effects smoother robot operation in the wall following mode.

It is a further object of this invention to provide a sensor subsystem for a robot which consumes a minimal amount of power.

It is a further object of this invention to provide a sensor subsystem which is unaffected by surfaces of different reflectivity.

The invention results from the realization that a low cost, accurate, and easy to implement system for either preventing an autonomous cleaning robot from driving off a stair or over an obstacle which is too high or too low and/or for more smoothly causing the robot to follow a wall for more thorough cleaning can be effected by intersecting the field of

view of a detector with the field of emission of a directed beam at a predetermined region and then detecting whether the floor or wall occupies that region. If the floor does not occupy the predefined region, a stair or some other obstacle is present and the robot is directed away accordingly. If a wall occupies the region, the robot is first turned away from the wall and then turned back towards the wall at decreasing radiuses of curvature until the wall once again occupies the region of intersection to effect smoother robot operation in the wall following mode.

This invention features an autonomous robot comprising a housing which navigates in at least one direction on a surface. A first sensor subsystem is aimed at the surface for detecting obstacles on the surface. A second sensor subsystem is aimed at least proximate the direction of navigation for detecting walls. Each subsystem includes an optical emitter which emits a directed beam having a defined field of emission and a photon detector having a defined field of view which intersects the field of emission of the emitter at a finite, predetermined region.

The robot obstacle detection system of this invention features a robot housing which navigates with respect to a surface and a sensor subsystem having a defined relationship with respect to the housing and aimed at the surface for detecting the surface. The sensor subsystem includes an optical emitter which emits a directed beam having a defined field of emission and a photon detector having a defined field of view which intersects the field of emission of the emitter at a region. A circuit in communication with the detector then redirects the robot when the surface does not occupy the region to avoid obstacles.

Typically, there are a plurality of sensor subsystems spaced from each other on the housing of the robot and the circuit includes logic for detecting whether any detector has failed to detect a beam from an emitter.

In one embodiment, the robot includes a surface cleaning brush. The emitter typically includes an infrared light source and the detector then includes an infrared photon detector. A modulator connected to the infrared light source modulates the directed infrared light source beam at a predetermined frequency and photon detector is tuned to that frequency. The emitter usually includes an emitter collimator about the infrared light source for directing the beam and the detector then further includes a detector collimator about the infrared photon detector. The emitter collimator and the detector collimator are preferably angled with respect to the surface to define a finite region of intersection.

The robot wall detection system of this invention includes a robot housing which navigates with respect to a wall and a sensor subsystem having a defined relationship with respect to the housing and aimed at the wall for detecting the presence of the wall. The sensor subsystem includes an emitter which emits a directed beam having a defined field of emission and a detector having a defined field of view which intersects the field of emission of the emitter at a region. A circuit in communication with the detector redirects the robot when the wall occupies the region.

In the preferred embodiment, there are a plurality of sensor subsystems spaced from each other on the housing of the robot and the circuit includes logic for detecting whether any detector has detected a beam from an emitter.

The circuit includes logic which redirects the robot away from the wall when the wall occupies the region and back towards the wall when the wall no longer occupies the region of intersection preferably at decreasing radiuses of curvature until the wall once again occupies the region of

intersection to effect smooth operation of the robot in the wall following mode.

The sensor subsystem for an autonomous robot which rides on a surface in accordance with this invention includes an optical emitter which emits a directed optical beam having a defined field of emission, a photon detector having a defined field of view which intersects the field of emission of the emitter at a region and a circuit in communication with a detector for providing an output when an object is not present in the region.

If the object is the surface, the output from the circuit causes the robot to be directed to avoid an obstacle. If, on the other hand, the object is a wall, the output from the circuit causes the robot to be directed back towards the wall.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects, features and advantages will occur to those skilled in the art from the following description of a preferred embodiment and the accompanying drawings, in which:

FIG. **1** is schematic view of a robot in accordance with the subject invention approaching a downward stair;

FIG. **2** is a schematic view of the same robot approaching an upward stair;

FIG. **3** is a schematic view of the same robot approaching an obstacle on a floor;

FIG. **4** is a schematic view showing the difference between the wall following and random modes of travel of a robot in accordance with the subject invention;

FIG. **5** is a schematic view of a sensor subsystem in accordance with one embodiment of the subject invention;

FIG. **6** is a schematic view of a sensor subsystem in accordance with another, preferred embodiment of the subject invention;

FIG. **7** is a schematic view showing the field of emission of the emitter and the field of view of the detector of the sensor subsystem shown in FIG. **6**;

FIG. **8** is a three dimensional schematic view showing a full overlap of the field of emission of the emitter and the field of view of the detector in accordance with the subject invention;

FIG. **9** is a three dimensional schematic view showing the situation which occurs when there is a minimal overlap between the field of emission and the field of view of the sensor subsystem of the subject invention;

FIG. **10** is a graph showing the relationship between the ratio of overlap area and the height of the sensor subsystem above the floor;

FIG. **11** is a series of views showing, from top to bottom, no overlap between the field of emission and the field of view and then a full overlap of the field of view over the field of emission;

FIG. **12** is a set of figures corresponding to FIG. **11** depicting the area of overlap for each of these situations shown in FIG. **11**;

FIG. **13** is a more detailed schematic view of the sensor subsystem according to the preferred embodiment of the subject invention;

FIG. **14** is a schematic view of the sensor subsystem of FIG. **13** in place on the shell or housing of a robot in accordance with the subject invention;

FIG. **15** is a schematic view of the wall detection system in accordance with the subject invention in place on the shell or housing of a robot;

FIG. **16** is a schematic three dimensional view of another embodiment of the sensor system in accordance with the subject invention;

FIG. **17** is a flow chart depicting the primary steps associated with a logic which detects whether a cliff is present in front of the robot in accordance with the subject invention;

FIG. **18** is a flow chart depicting the primary steps associated with the logic of the wall detection mode of operation of the robot in accordance with the subject invention;

FIG. **19** is a bottom view of a cleaning robot in accordance with the subject invention configured to turn about curvatures of decreasing radiuses;

FIG. **20** is a schematic top view showing the abrupt turns made by a robot in the wall following mode when the wall following algorithm of the subject invention is not employed;

FIG. **21** is a view similar to FIG. **20** except that now the wall following algorithm of the subject invention is employed to smooth out the path of the robotic cleaning device in the wall following mode;

FIG. **22** is a block diagram showing the primary components associated with a complete robotic cleaning device;

FIG. **23** is a schematic three dimensional view of a robotic cleaning device employing a number of cliff sensors and wall sensors in accordance with the subject invention;

FIG. **24** is a bottom view of one particular robotic cleaning device and the cliff sensors incorporated therewith in accordance to the subject invention;

FIG. **25** is a side view of the same robot further incorporating wall following sensors in accordance with the subject invention;

FIG. **26** is a circuit diagram for the detector circuit of the subject invention;

FIG. **27** is a circuit diagram for the oscillator circuit of the subject invention;

FIG. **28** is a circuit diagram for the power connection circuit of the subject invention;

FIG. **29** is the decoupling circuit of the subject invention;

FIG. **30** is a diagram of a connector used in the subject invention;

FIG. **31** is a diagram of another connector;

FIG. **32** is a diagram of still another connector;

FIG. **33** is a circuit diagram of a jumper used in the subject invention; and

FIG. **34** is a circuit diagram for constant current source used in the subject invention.

DISCLOSURE OF THE PREFERRED EMBODIMENT

Robotic cleaning device **10**, FIG. **1** can be configured to dust, mop, vacuum, and/or sweep a surface such as a floor. Typically, robot **10** operates in two modes: random coverage and a wall following mode as discussed in the Background section above. In either mode, robot **10** may encounter downward stair **12** or another similar "cliff", upward stair **14**, FIG. **2** or another similar rise, and/or obstacle **16**, FIG. **3**. According to one specification, the robot must be capable of traversing obstacles less then ⅝" high or low. Therefore, robot **10** must avoid stairs **12** and **14** but traverse obstacle **16** which may be an extension cord, the interface between a rug and hard flooring, or a threshold between rooms.

As delineated in the background of the invention, presently available obstacle sensor subsystems useful in connection with robot **10** are either too complex or too expensive or both. Moreover, robot **10**, FIG. **4** is designed to be inexpensive and to operate based on battery power to thus thoroughly clean room **20** in two modes: a wall following mode as shown at **22** and **24** and a random bounce mode as shown at **26**. In the wall following mode, the robot follows the wall for a time. In the random bounce mode, the robot travels in a straight line until it bumps into an object. It then turns away from the obstacle by a random turn and then continues along in a straight line until the next object is encountered.

Accordingly, any obstacle sensor subsystem must be inexpensive, simple in design, reliable, must not consume too much power, and must avoid certain obstacles but properly recognize and traverse obstacles which do not pose a threat to the operation of the robot.

Although the following disclosure relates to cleaning robots, the invention hereof is not limited to such devices and may be useful in other devices or systems wherein one or more of the design criteria listed above are important.

In the simplest embodiment, sensor subsystem **50**, FIG. **5** according to this invention includes optical emitter **52** which emits a directed beam **54** having a defined field of emission explained supra. Sensor subsystem **50** also includes photon detector **56** having a defined field of view which intersects the field of emission of emitter **52** at or for a given region. Surface **58** may be a floor or a wall depending on the arrangement of sensor subsystem **50** with respect to the housing of the robot.

In general, for obstacle avoidance, circuitry is added to the robot and connected to detector **56** to redirect the robot when surface **58** does not occupy the region defining the intersection of the field of emission of emitter **52** and the field of view of detector **56**. For wall following, the circuitry redirects the robot when the wall occupies the region defined by the intersection of the field of emission of emitter **52** and the field of view of detector **56**. Emitter collimator tube **60** forms directed beam **54** with a predefined field of emission and detector collimator tube **62** defines the field of view of the detector **56**.

One potential problem with the configuration shown in FIG. **5** is that the difference between a white or highly reflective surface a long distance away from subsystem **50** and a black or non-reflective surface closer to subsystem **50** cannot be easily detected by the control circuitry. Moreover, the effects of specular scattering are not always easily compensated for adequately when the beam from emitter **52** is directed normal to the plane of surface **58**.

Accordingly, in the preferred embodiment, emitter collimator **60'**, FIG. **6** and detector collimator **62'** are both angled with respect to surface **58** and with respect to each other as shown. In this way, the region **70**, FIG. **7** in which the field of emission of emitter **52'** as shown at **72** and the field of view of detector of **56'** as shown at **74** intersect is finite to more adequately address specular scattering and surfaces of different reflectivity. In this design, the emitter is typically an infrared emitter and the detector is typically an infrared radiation detector. The infrared energy directed at the floor decreases rapidly as the sensor-to-floor distance increases while the infrared energy received by the detector changes linearly with surface reflectivity.

The sensor subsystem is calibrated such that when floor or surface **58'**, FIG. **8** is the "normal" or expected distance with respect to the robot, there is a full or a nearly full overlap between the field of emission of the emitter and the field of view of the detector as shown. When the floor or surface is too far away such that the robot can not successfully traverse an obstacle, there is no or only a minimal overlap between the field of emission of the emitter and the field of view of the detector as shown in FIG. **9**. The emitter beam and the detector field of view are collimated such that they fully overlap only in a small region at the expected position of the floor. The detector threshold is then set so that the darkest available floor material is detected when the beam and the field of view fully overlap. As the robot approaches a cliff, the overlap decreases until the reflected intensity is below the preset threshold. This triggers cliff avoidance behavior. Highly reflective floor material delays the onset of cliff detection only slightly. By arranging the emitter and detector at 45° with respect to the floor, the region of overlap as a function of height is minimized. Equal incidence and reflection angles ensure that the cliff detector functions regardless of whether the floor material is specular or diffuse. The size of the overlap region can be selected by choosing the degree of collimation and the nominal distance to the floor.

In this way, the logic interface between the sensor subsystem and the control circuitry of the robot is greatly simplified. As shown in the table of FIG. **10**, when the displaced height is zero, that is the height of the sensor above the floor is nominal (e.g., 0.058 inches), the ratio of the area of overlap of the field of view and the field of emission is set at one but decreases almost linearly until there is no overlap at a displaced height equal to the maximum height obstacle the robot can successfully traverse (in this example a displaced distance of 0.050 inches). Thus, the overlap area is a function of the height of the sensor subsystem from the surface.

By tuning the system to simply redirect the robot when there is no detectable overlap, i.e., when the detector fails to emit a signal, the logic interface required between the sensor subsystem and the control electronics (e.g., a microprocessor) is simple to design and requires no or little signal conditioning. The emitted IR beam may be modulated and the return beam filtered with a matching filter in order to provide robust operation in the presence of spurious signals, such as sunlight, IR-based remote control units, fluorescent lights, and the like. Conversely, for the wall sensor embodiment, the system is tuned to redirect the robot when there is a detectable overlap.

FIGS. 11–12 provide in graphical form an example of the differences in the area of overlap depending on the height (d) of the sensor subsystem from a surface. The field of emission of the emitter and the field of view of the detector were set to be equal and non-overlapping at a distance (d) of 1.3 inches and each was an ellipse 0.940 inches along the major diameter and 0.650 inches along minor diameter. A full overlap occurred at d=0.85 inches where the resulting overlapping ellipses converge into a single ellipse 0.426 inches along the minor diameter and 0.600 inches along the major diameter. Those skilled in the art will understand how to adjust the field of emission and the field of view and the intersection region between the two to meet the specific design criteria of any robotic device in question. Thus, FIGS. **11** and **12** provide illustrative examples only.

In one embodiment, as shown in FIG. **13**, housing **80** of the sensor subsystem was rectangular 22 mm by 53 mm. 3 mm diameter plastic emitter collimator tube **82** and 3 mm diameter plastic detector collimator tube **84** were placed 13.772 mm from the bottom of housing **80** which was flush with the bottom of the shell of the robot. This configuration defined field of view and field of emission cones of 20°

placed at a 60° angle from each other. The angle between the respective collimator tubes was 60° and they were spaced 31.24 mm apart.

This configuration defined a region of intersection between the field of emission and the field of view 29.00 mm long beginning at the bottom of the robot.

In the design shown in FIG. **14**, the sensor subsystem is shown integrated with robot shell or housing **90** with a wheel (not shown) which supports the bottom **92** of shell **90** one half an inch above surface or floor **94**. The region of overlap of the field of view and the field of emission was 0.688 inches, 0.393 inches above. Thus, if stair **96** has a rise greater than 0.393 inches, no signal will be output by the detector and the robot redirected accordingly. In the preferred embodiment, the emitter includes an infrared light source and the detector includes an infrared photon detector each disposed in round plastic angled collimators.

For wall detection, emitter **102** and detector **100** are arranged as shown in FIG. **15**. The optical axes of the emitter and detector are parallel to the floor on which the robot travels. The field of emission of the emitter and the field of view of the detector are both 22 degree cones. A three millimeter diameter tube produces a cone of this specification when the active element is mounted 0.604 inches from the open end as shown. The optical axes of the emitter and detector intersect at an angle of 80 degrees. The volume of intersection **103** occurs at a point about 2.6 inches ahead of the point of tangency between the robot shell **106** and the wall **104** when the robot is travelling parallel to the wall. The line bisecting the intersection of the optical axes of the emitter and detector is perpendicular to the wall. This ensures that reflections from specular walls are directed from the emitter into the detector.

In another embodiment, detector **116**, FIG. **16** is positioned above emitter **112** and lens **118** with two areas of different curvature **116** and **114** used to focus light from emitter **112** to the same spot as the field of view of detector **116** at only one height above surface **120** so that if the height changes, there is no or at least not a complete overlap between the field of view of detector **116** and emitter **112** as defined by curvature areas **116** and **114**. In this situation, the rapid change of reflected intensity with height is provided by focusing two lenses on a single spot. When the floor is in the nominal position relative to the sensor subsystem, the emitter places all its energy on a small spot. The detector is focused on the same spot. As the floor falls away from the nominal position, light reflected into the detector (now doubly out of focus) decreases rapidly. By carefully selecting the lens-to-floor distance and the focal lengths of the two lenses, it is possible for the emitter and detector to be located at different points but have a common focus on the floor.

The logic of the circuitry associated with the cliff sensor embodiment modulates the emitter at a frequency of several kilohertz and detects any signal from the detector, step **150**, FIG. **17**, which is tuned to that frequency. When a signal is not output by the detector, step **152**, the expected surface is not present and no overlap is detected. In response, an avoidance algorithm is initiated, step **17** to cause the robot to avoid any interfering obstacle. When a reflected signal is detected, processing continues to step **150**.

In the wall detection mode, the logic of the circuitry associated with the sensor subsystem modulates the emitter and detects signals from the detector as before, step **170**, FIG. **18** until a reflection is detected, step **172**. A wall is then next to the robot and the controlling circuitry causes the robot to turn away from the wall, step **174** and then turn back, step **176** until a reflection (the wall) is again detected, step **178**. By continuously decreasing the radius of curvature of the robot, step **180**, the path of the robot along the wall in the wall following mode is made smoother.

As shown in FIG. **19**, robot housing **200** includes three wheels **202**, **204**, and **206** and is designed to only move forward in the direction shown by vector **208**. When a wall is first detected (step **172**, FIG. **18**), the robot turns away from the wall in the direction of vector **210** and then turns back towards the wall rotating first about radius R_1 and then about radius R_2 and then about smoothly decreasing radius points (steps **178–180**, FIG. **18**) until the wall is again detected.

As shown in FIG. **20**, if only one constant radius of curvature was chosen, the robot's travel path along the wall would be a series of abrupt motions. In contrast, by continuously reducing the radius of curvature as the robot moves forward back to the wall in accordance with the subject invention, the robot's travel path along the wall is smooth as shown in FIG. **21**.

For reasons of cleaning thoroughness and navigation, the ability to follow walls is essential for cleaning robots. Dust and dirt tend to accumulate at room edges. The robot therefore follows walls that it encounters to insure that this special area is well cleaned. Also, the ability to follow walls enables a navigation strategy that promotes full coverage. Using this strategy, the robot can avoid becoming trapped in small areas. Such entrapments could otherwise cause the robot to neglect other, possibly larger, areas.

But, it is important that the detected distance of the robot from the wall does not vary according to the reflectivity of the wall. Proper cleaning would not occur if the robot positioned itself very close to a dark wall but several inches away from a light colored wall. By using the dual collimation system of the subject invention, the field of view of the infrared emitter and detector are restricted in such a way that there is a limited, selectable volume where the cones of visibility intersect. Geometrically, the sensor is arranged so that it can detect both diffuse and specular reflection. This arrangement allows the designer to select with precision the distance at which the robot follows the wall independent of the reflectivity of the wall.

A more complete robot system **300**, FIG. **22** in accordance with this invention includes a circuit embodied in microprocessor **302** which controls drive motion subsystem **304** of robot **300** in both the random movement and wall following modes to drive and turn the robot accordingly. Sensor subsystem **308** represents the designs discussed above with respect to FIGS. **6–16**. The detectors of each such subsystem provide an output signal to microprocessor **302** as discussed supra which is programmed according to the logic discussed with reference to FIGS. **17–18** to provide the appropriate signals to drive subsystem **304**. Modulator circuitry **310** drives the emitters of the sensor subsystem **308** under the control of processor **302** as discussed above.

Typically, there are three or more cliff detector subsystems as shown in FIG. **23** at locations **316**, **318**, and **320** spaced about the forward bottom portion of the robot and aimed downward and only one or two or more wall detector subsystems at locations **322** and **324** spaced about the forward portion of the robot housing and aimed outwardly.

In one embodiment, 12 inch diameter three wheeled differentially steered robot **340**, FIG. **24** is a sweeper type cleaning robot equipped with sweeping brush **342** and includes four cliff detector subsystems **342**, **344**, **346**, and **348** and one wall detector subsystem **352**, FIG. **25**. The

output of the detectors of each subsystem are typically connected together by "OR" circuitry logic so that when any one detector detects a signal it is communicated to the processor.

FIG. **26** shows one embodiment of a detector circuit. R1 (**384**), CR1 (**382**), R2 (**388**), R3 (**390**), C1 (**392**), and U1:D (**394**) form a voltage reference used to prevent saturation of intermediate gain stages. In this embodiment, R1 (**384**) and CR1 (**382**) create from the input voltage (**386**) approximately 5.1V that is divided by voltage divider R2 (**388**), R3 (**390**) to create a voltage of approximately 1.8V. This is buffered by U1:D (**394**) configured as a unity gain follower. C1 (**392**) is provided to reduce noise. The photo-transistor (not shown) used in this embodiment requires a biasing current, provided from the above described reference voltage through R7 (**396**). R10 (**398**), R13 (**402**), and U1:A (**400**) implement an amplifier with a gain of approximately −10. C4 (**404**) is provided for compensation and to reduce noise.

C2 (**404**) is used to block any DC component of the signal, while R8 (**407**), R12 (**408**), and U1:B (**406**) implement an amplifier with a gain of approximately −100. CR2 (**410**), R5 (**414**), and C3 (**416**) implement a peak detector/rectifier. R11 (**412**) provides a discharge path for C3 (**416**). The output of this peak detector is then compared to the above mentioned reference voltage by U1:C (**420**). R4 (**422**) provide hystersis. R9 (**424**) is a current limiting resistor used so that the output of U1:C (**420**) may be used to drive an indicator LED (not shown). Jumper JU1 (**426**) provides a convenient test point for debugging.

An oscillator circuit as shown in FIG. **27** is used to modulate the emitter IR LED at a frequency of several KHz. The exact frequency may be selected by adjusting R23 (**468**). Those skilled in the art will immediately deduce other ways of obtaining the same function. The simple filter/amplifier circuit of FIG. **26** is used to receive and amplify the output of a photo-transistor (not shown). A peak detector/integrator is used to convert the AC input to a threshold measurement. If sufficient energy in the selected bandwidth is received, the output signal is present at (**428**) is driven to a logical high state. Those skilled in the art will immediately recognize other ways of achieving the same ends. Components R14 (**440**), R17 (**446**), and U2:B (**448**) create a buffered bias voltage equal to approximately one-half of the input voltage (**442**). U2:A (**456**), R19 (**460**), R23 (**468**), and C5 (**470**) create a simple oscillator of a form commonly used. R18 (**458**), Q1 (**462**), and R21 (**466**) convert the voltage mode oscillations of the oscillator described to current-mode oscillations in order that the emitter LED (connected to **464**) be relatively constant current regardless of power supply voltage (**442**). The actual current impressed through the circuit may be altered to meet the requirements of the chosen LED by varying the value of R21 (**466**).

In FIG. **28**, a connector J1 (**500**) is used to connect the system to a means of supplying power (e.g., a battery). Fuse F1 (**501**) is included to limit excessive current flow in the event of a short circuit or other defect. Capacitors C6 (**506**) and C7 (**510**), FIG. **29** are provided for decoupling of other electronics (U1 and U2). Connector J2 (**514**), FIG. **30** provides a means of attachment for the IR LED transmitter (not shown). Connector J3 (**520**), FIG. **31** provides a means of attachment for the IR photo-transistor (not shown). Connector J4 (**530**), FIG. **32** provides a means of attachment for an indicator LED (to indicate the presence or absence of an obstacle, a means of attachment for a battery (not shown), and a means of attachment for a recharging power supply (not shown). Jumper JU2, FIG. **33**, provides a convenient GROUND point for test equipment, etc. U3 (**536**) and R22 (**538**), FIG. **34** implements a constant-current source used in recharging an attached NiCad battery. U3 maintains a constant 5 volts between pins 3 and 2.5 volts divided by 22 Ohms (R22) creates a current of approximately 230 mA.

In other embodiments, a fiber optic source and detector may be used which operate similar to the sensor subsystems described above. The difference is that collimation is provided by the acceptance angle of two fiber optic cables. The fiber arrangement allows the emitter and detector to be located on a circuit board rather than mounted near the wheel of the robot. The cliff detector and wall detector can also be implemented using a laser as the source of the beam. The laser provides a very small spot size and may be useful in certain application where the overall expense is not a priority design consideration. Infrared systems are preferred when cost is a primary design constraint. Infrared sensors can be designed to work well with all floor types, they are inexpensive, and can be fitted into constrained spaces.

Although specific features of the invention are shown in some drawings and not in others, this is for convenience only as each feature may be combined with any or all of the other features in accordance with the invention. The words "including", "comprising", "having", and "with" as used herein are to be interpreted broadly and comprehensively and are not limited to any physical interconnection. Moreover, any embodiments disclosed in the subject application are not to be taken as the only possible embodiments.

Other embodiments will occur to those skilled in the art and are within the following claims:

What is claimed is:

1. A robot obstacle detection system comprising:
- a robot housing which navigates with respect to a surface;
- a sensor subsystem having a defined relationship with respect to the housing and aimed at the surface for detecting the surface, the sensor subsystem including:
  - an optical emitter which emits a directed beam having a defined field of emission, and
  - a photon detector having a defined field of view which intersects the field of emission of the emitter at a finite region; and
- a circuit in communication with the detector for redirecting the robot when the surface does not occupy the region to avoid obstacles.

2. The system of claim **1** further including a plurality of sensor subsystems spaced from each other on the housing of the robot, the circuit including logic for detecting whether any detector of each said sensor subsystem has failed to detect a beam from an emitter.

3. The system of claim **1** in which the robot includes a surface cleaning brush.

4. The system of claim **1** in which the emitter includes an infrared light source and the detector includes an infrared photon detector.

5. The system of claim **4** further including a modulator connected to the infrared light source for modulating the directed infrared light source beam at a predetermined frequency.

6. The system of claim **5** in which the infrared photon detector is tuned to the said predetermined frequency.

7. The system of claim **4** in which the emitter further includes an emitter collimator about the infrared light source for directing the beam and in which the detector further includes a detector collimator about the infrared photon detector to define the field of view.

8. The system of claim **7** in which the emitter collimator and the detector collimator are angled with respect to the surface to define a finite region of intersection.

9. A robot wall detection system comprising:

a robot housing which navigates with respect to a wall;

a sensor subsystem having a defined relationship with respect to the housing and aimed at the wall for detecting the presence of the wall, the sensor subsystem including:

an emitter which emits a directed beam having a defined field of emission, and

a detector having a defined field of view which intersects the field of emission of the emitter at a region; and

a circuit in communication with the detector for redirecting the robot when the wall occupies the region.

10. The system of claim 9 further including a plurality of sensor subsystems spaced from each other on the housing of the robot, the circuit including logic for detecting whether any detector of any said sensor subsystem has detected a beam from an emitter.

11. The system of claim 9 in which the robot includes a surface cleaning brush.

12. The system of claim 9 in which the emitter includes an infrared light source and the detector includes an infrared photon detector.

13. The system of claim 12 further including a modulator connected to the infrared light source for modulating the directed infrared light beam at a predetermined frequency.

14. The system of claim 13 in which the infrared photon detector is tuned to the predetermined frequency.

15. The system of claim 12 in which the emitter farther includes an emitter collimator about the infrared light source for directing the beam and in which the detector further includes a detector collimator about the infrared photon detector to define the field of view.

16. The system of claim 15 in which the emitter collimator and the detector collimator are angled with respect to surface.

17. The system of claim 9 in which the circuit includes logic which redirects the robot away from the wall when the wall occupies the region and back towards the wall when the wall no longer occupies the region of intersection.

18. The system of claim 9 in which the circuit includes logic which redirects the robot away from the wall when the wall occupies the region and then back towards the wall when the wall no longer occupies the region of intersection at decreasing radiuses of curvature until the wall once again occupies the region of intersection.

19. An autonomous robot comprising:

a housing which navigates in at least one direction on a surface;

a first sensor subsystem aimed at the surface for detecting obstacles on the surface; and

a second sensor subsystem aimed at least proximate the direction of navigation for detecting walls, each said subsystem including:

an optical emitter which emits a directed beam having a defined field of emission and a photon detector having a defined field of view which intersects the field of emission of the emitter at a finite, predetermined region.

20. A sensor subsystem for an autonomous robot which rides on a surface, the sensor subsystem comprising:

an optical emitter which emits a directed optical beam having a defined field of emission;

a photon detector having a defined field of view which intersects the field of emission of the emitter at a region; and

a circuit in communication with the detector for providing an output when a wall is not present in the region, wherein the output from the circuit causes the robot to be directed back towards the wall when the wall does not occupy the region of intersection of the defined field of emission of the emitter and the defined field of view of the detector.

* * * * *

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(12) United States Patent
Jones et al.

(10) Patent No.: **US 6,809,490 B2**
(45) Date of Patent: **Oct. 26, 2004**

(54) **METHOD AND SYSTEM FOR MULTI-MODE COVERAGE FOR AN AUTONOMOUS ROBOT**

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(73) Assignee: **iRobot Corporation**, Burlington, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/167,851**

(22) Filed: **Jun. 12, 2002**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**[7] **B25J 5/00**

(52) **U.S. Cl.** **318/568.12**; 318/568.16; 318/568.17; 700/245

(58) **Field of Search** 318/568.12, 568.16, 318/568.17; 700/245

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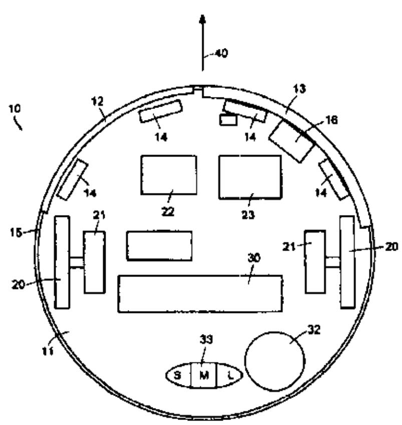
Primary Examiner—Rita Leykin
(74) *Attorney, Agent, or Firm*—Glen D. Weinstein, Esq.; Gesmer Updegrove LLP

(57) **ABSTRACT**

A control system for a mobile robot (**10**) is provided to effectively cover a given area by operating in a plurality of modes, including an obstacle following mode (**51**) and a random bounce mode (**49**). In other embodiments, spot coverage, such as spiraling (**45**), or other modes are also used to increase effectiveness. In addition, a behavior based architecture is used to implement the control system, and various escape behaviors are used to ensure full coverage.

42 Claims, 16 Drawing Sheets



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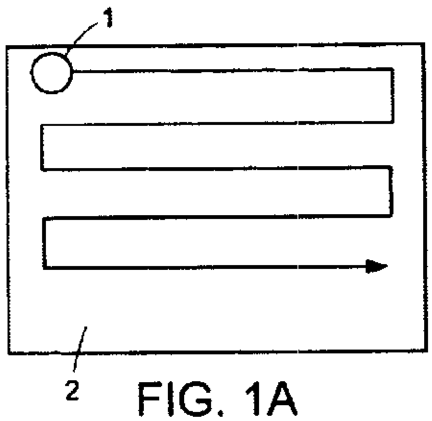


FIG. 1A

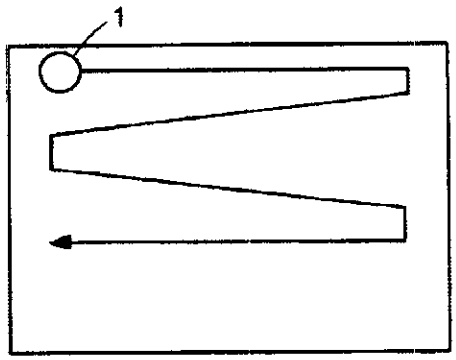


FIG. 1B

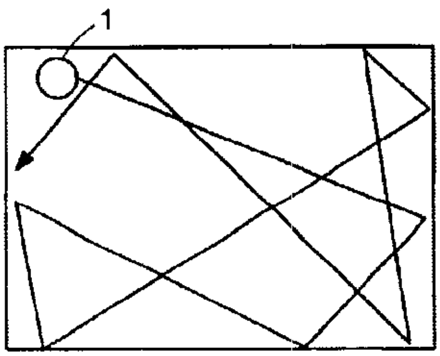


FIG. 1C

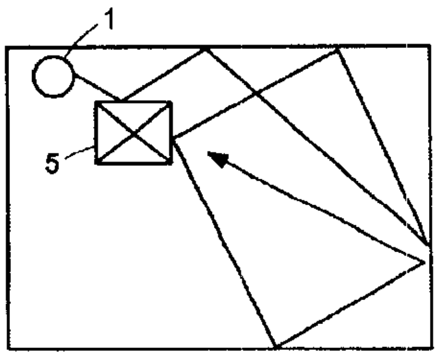


FIG. 1D

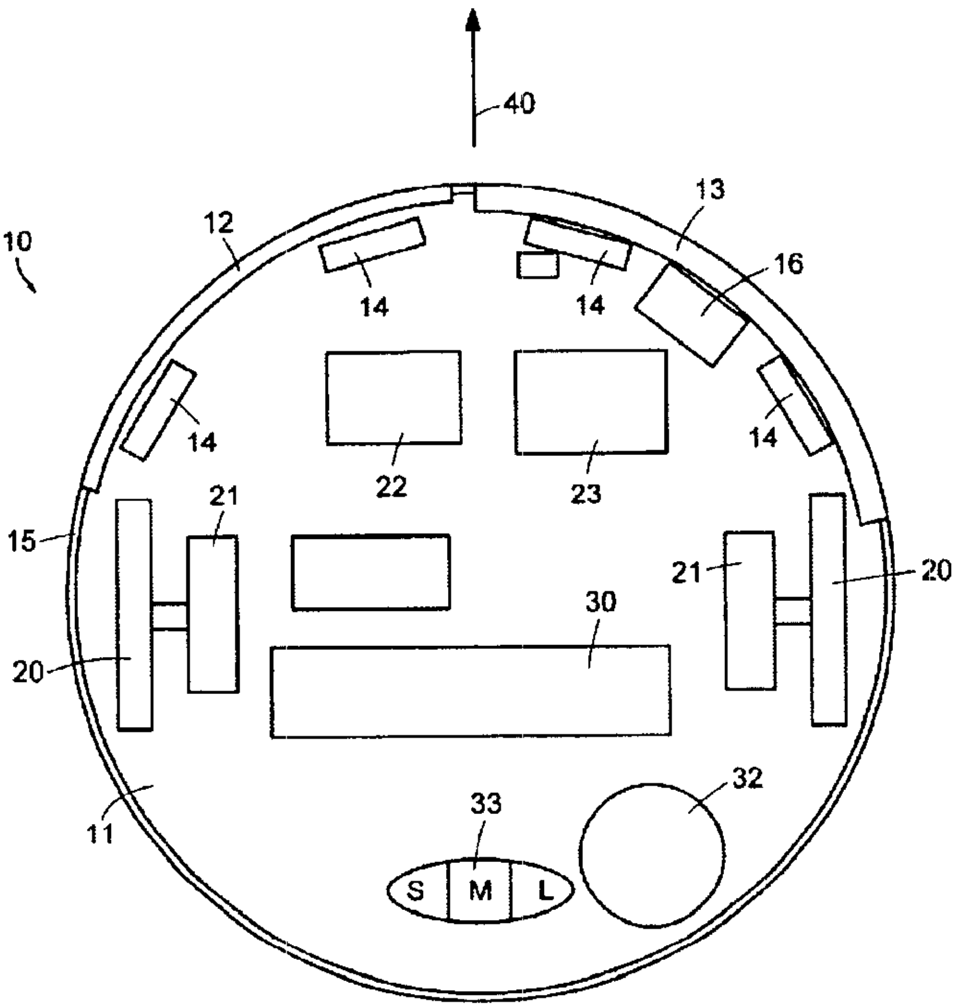


FIG. 2

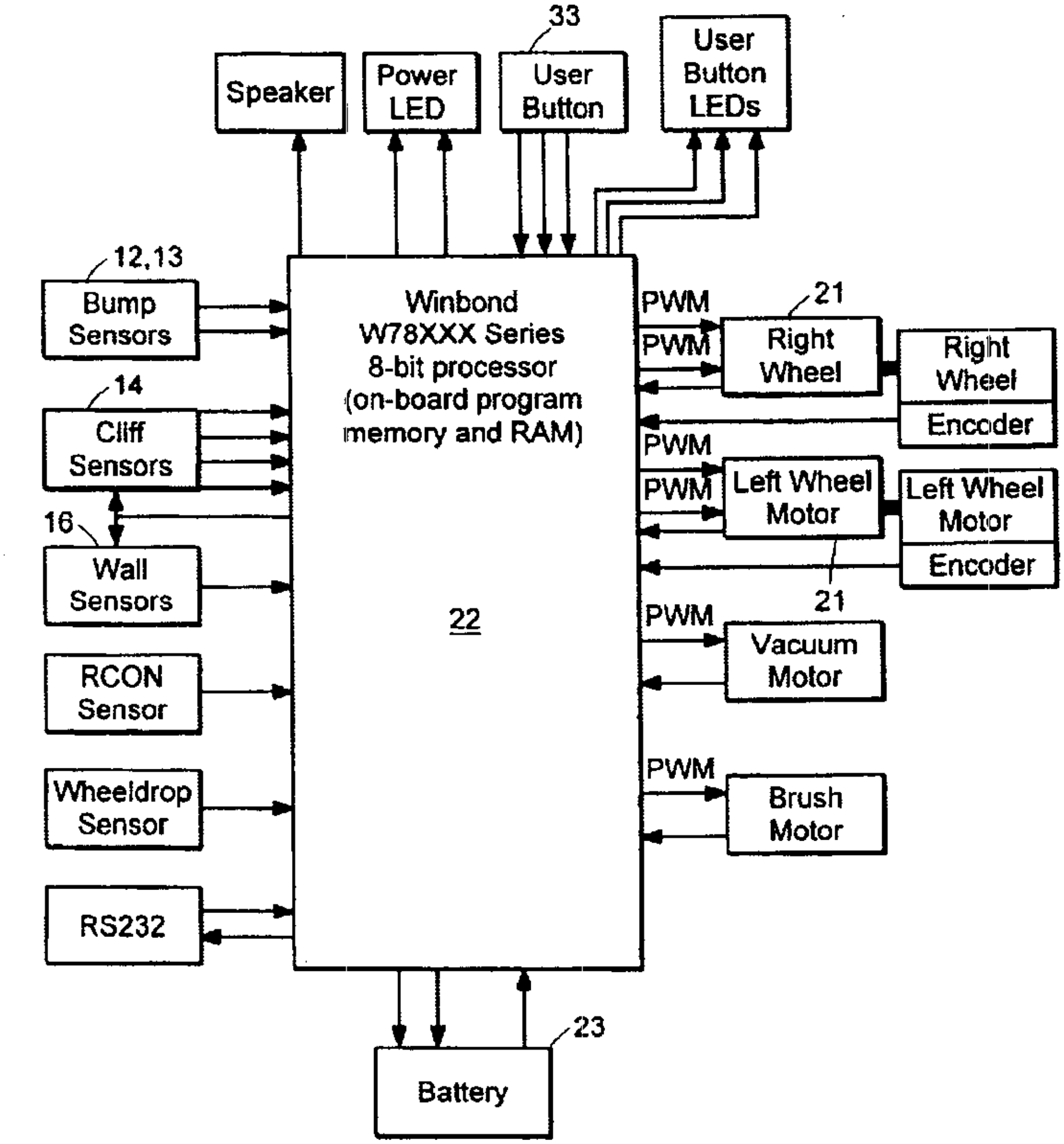

Speaker
Power LED
33
User Button
User Button LEDs
12,13
Bump Sensors
14
Cliff Sensors
16
Wall Sensors
RCON Sensor
Wheeldrop Sensor
RS232
Winbond W78XXX Series 8-bit processor (on-board program memory and RAM)
22
PWM
21
Right Wheel
Right Wheel
Encoder
PWM
Left Wheel Motor
Left Wheel Motor
Encoder
21
PWM
Vacuum Motor
PWM
Brush Motor
23
Battery

FIG. 3

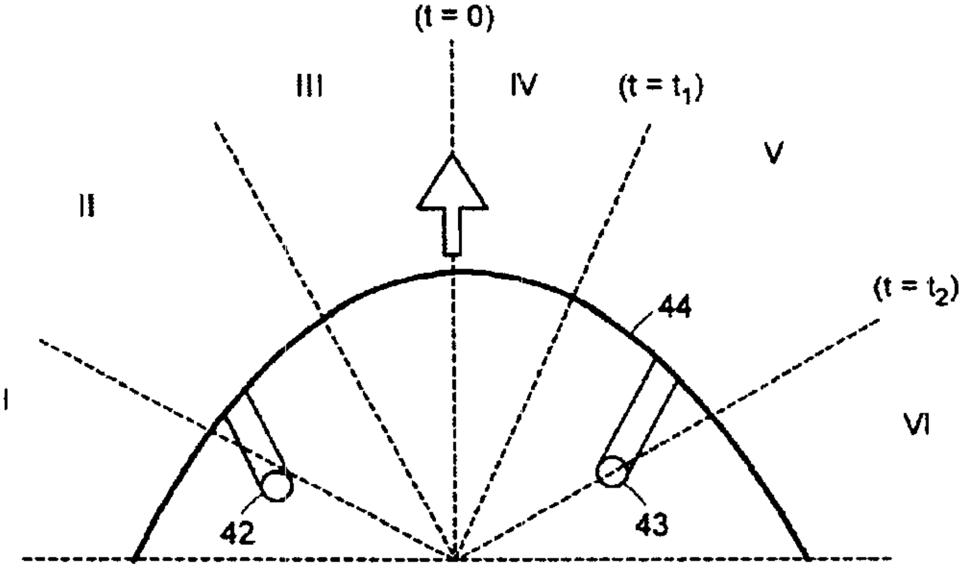


FIG. 4A

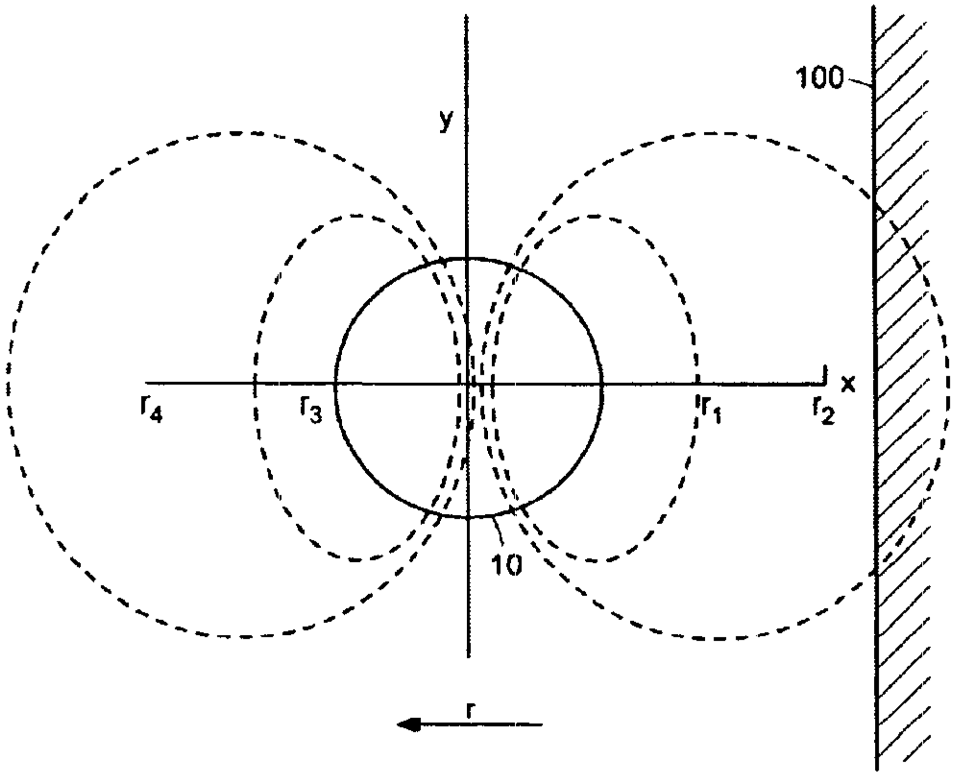


FIG. 4B

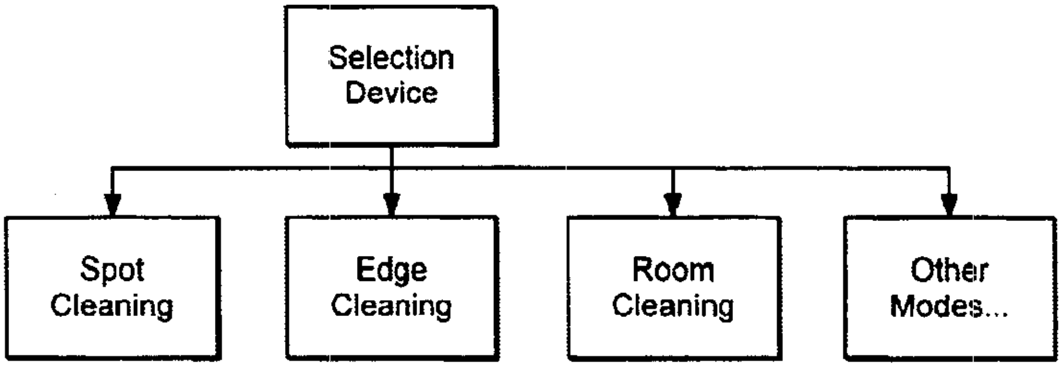


FIG. 5

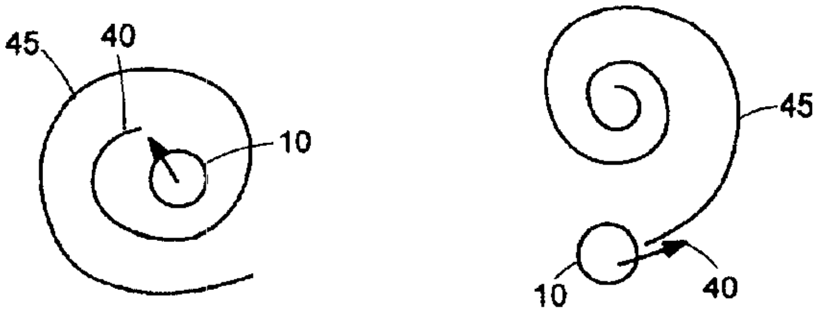


FIG. 6A FIG. 6B

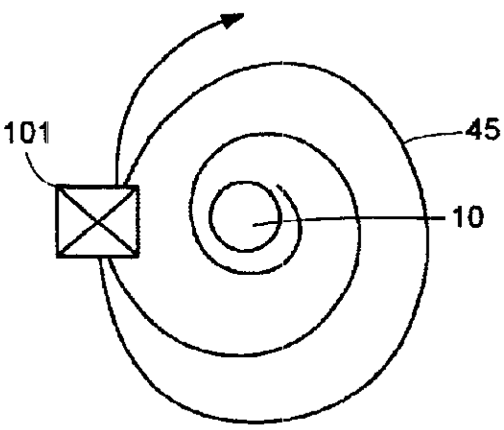
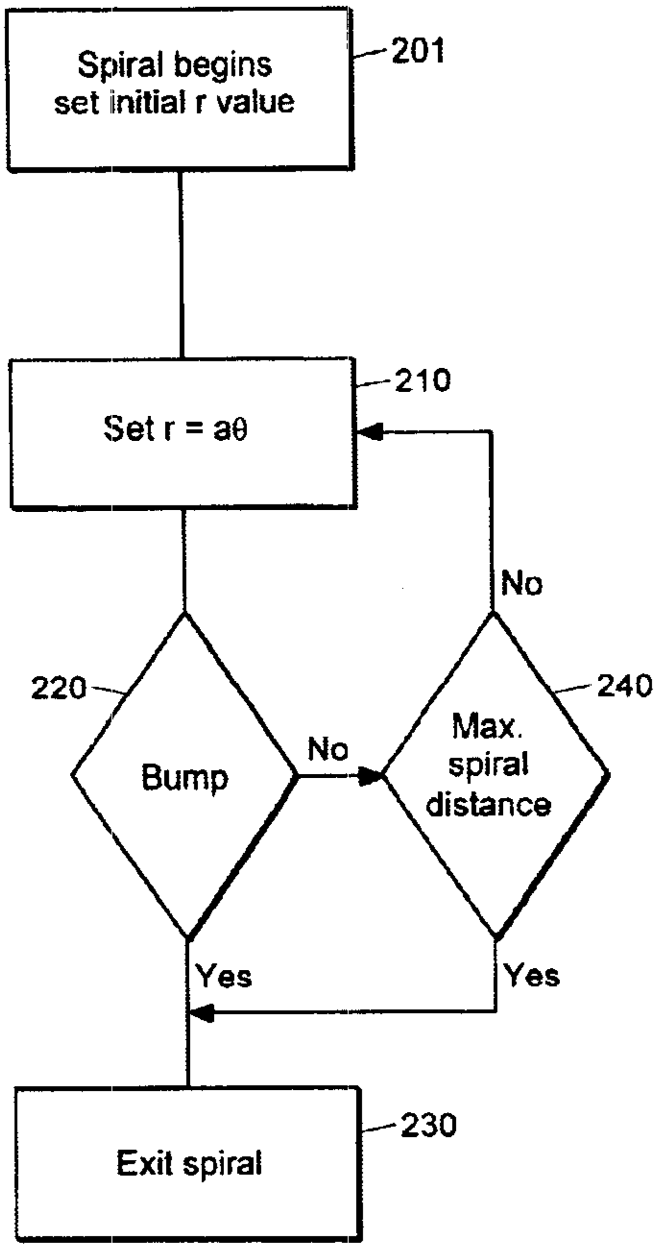


FIG. 6C



Spiral begins
set initial r value
201
Set r = aθ
210
No
220
Bump
No
Max.
spiral
distance
240
Yes
Yes
Exit spiral
230

FIG. 7

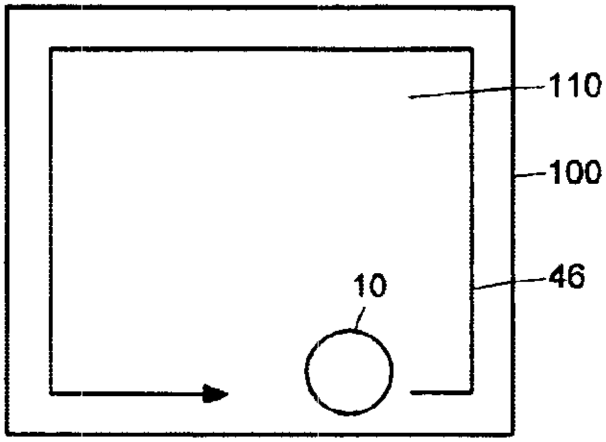


FIG. 8A

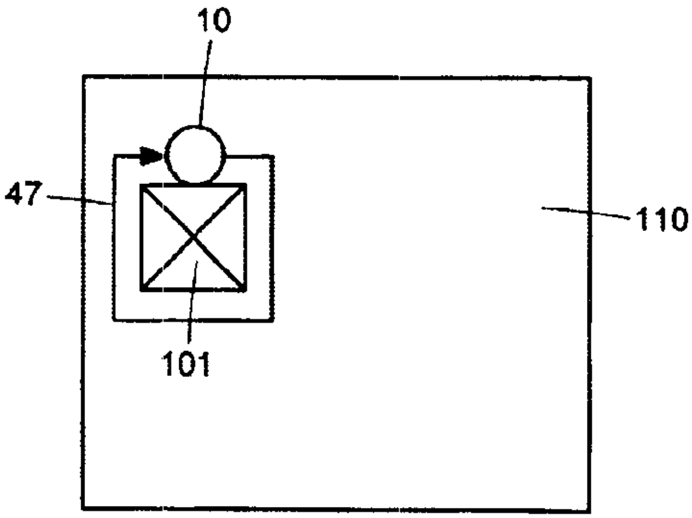


FIG. 8B

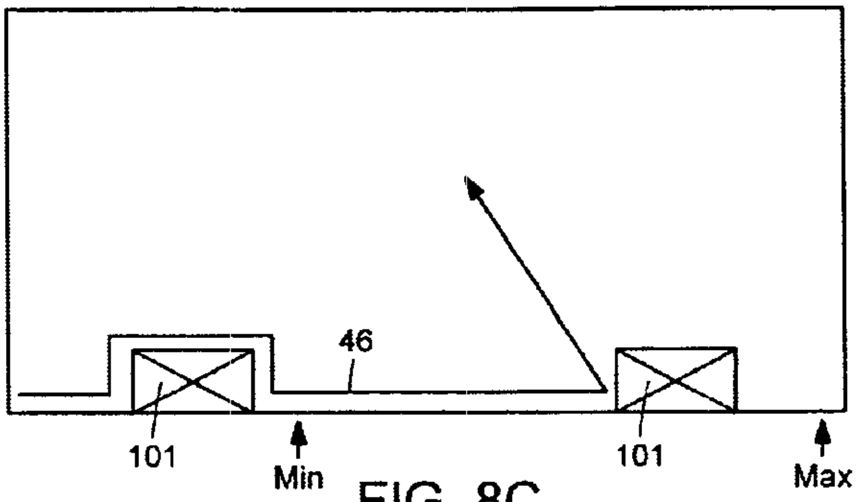


FIG. 8C

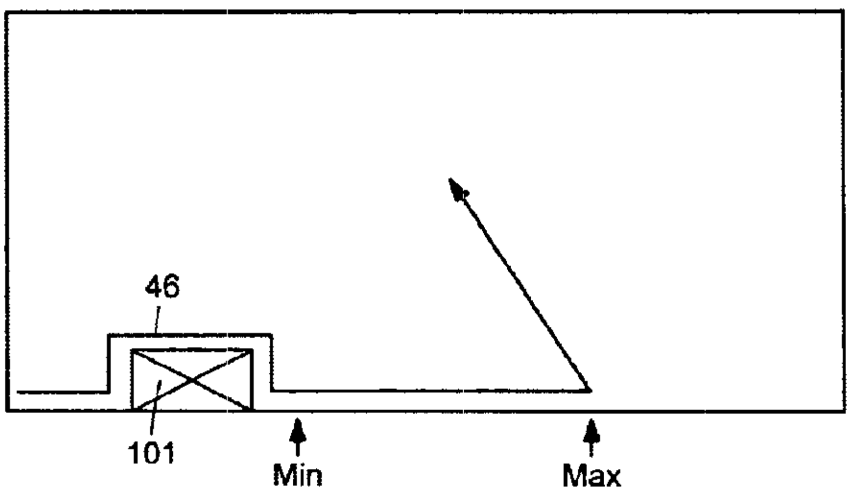


FIG. 8D

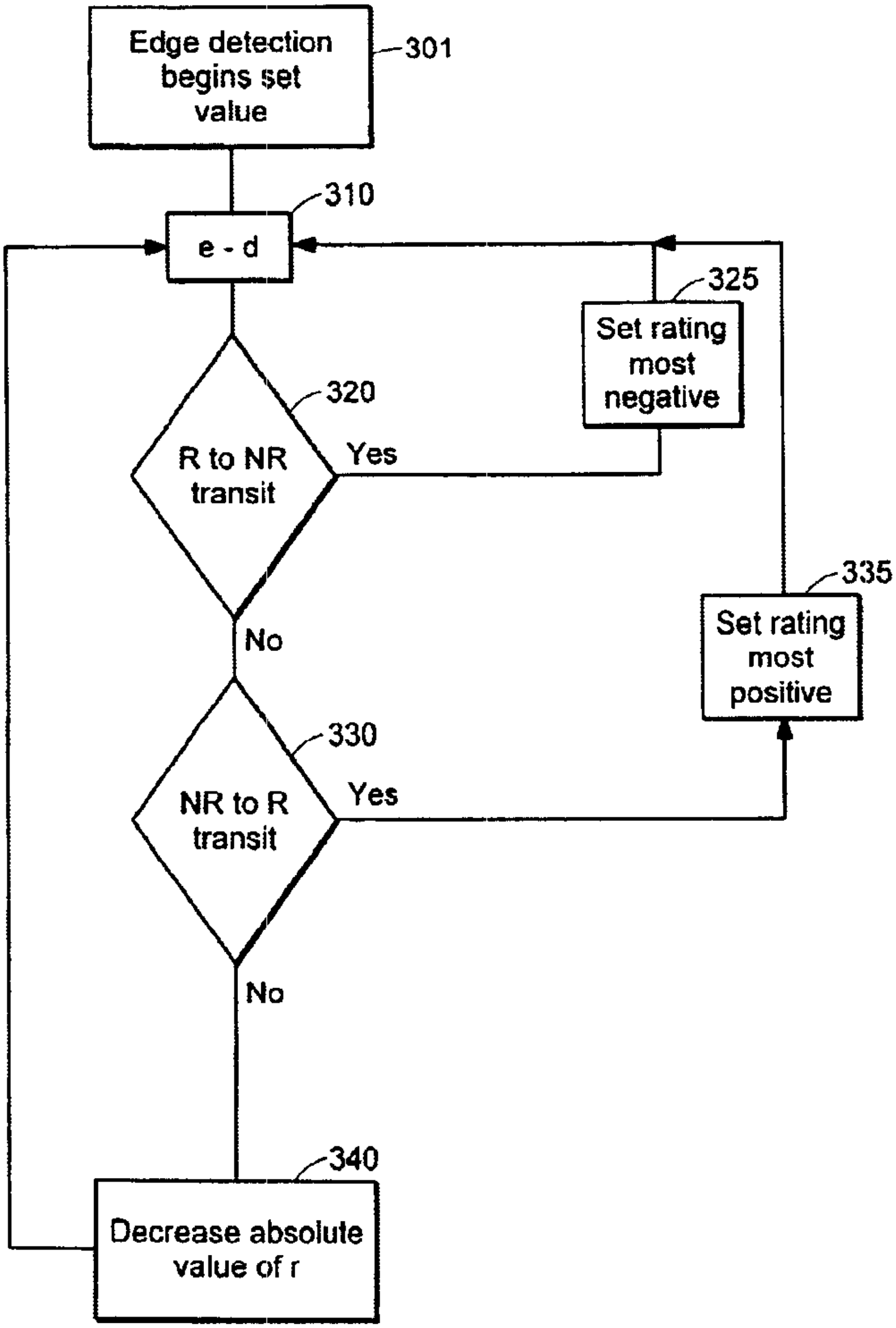
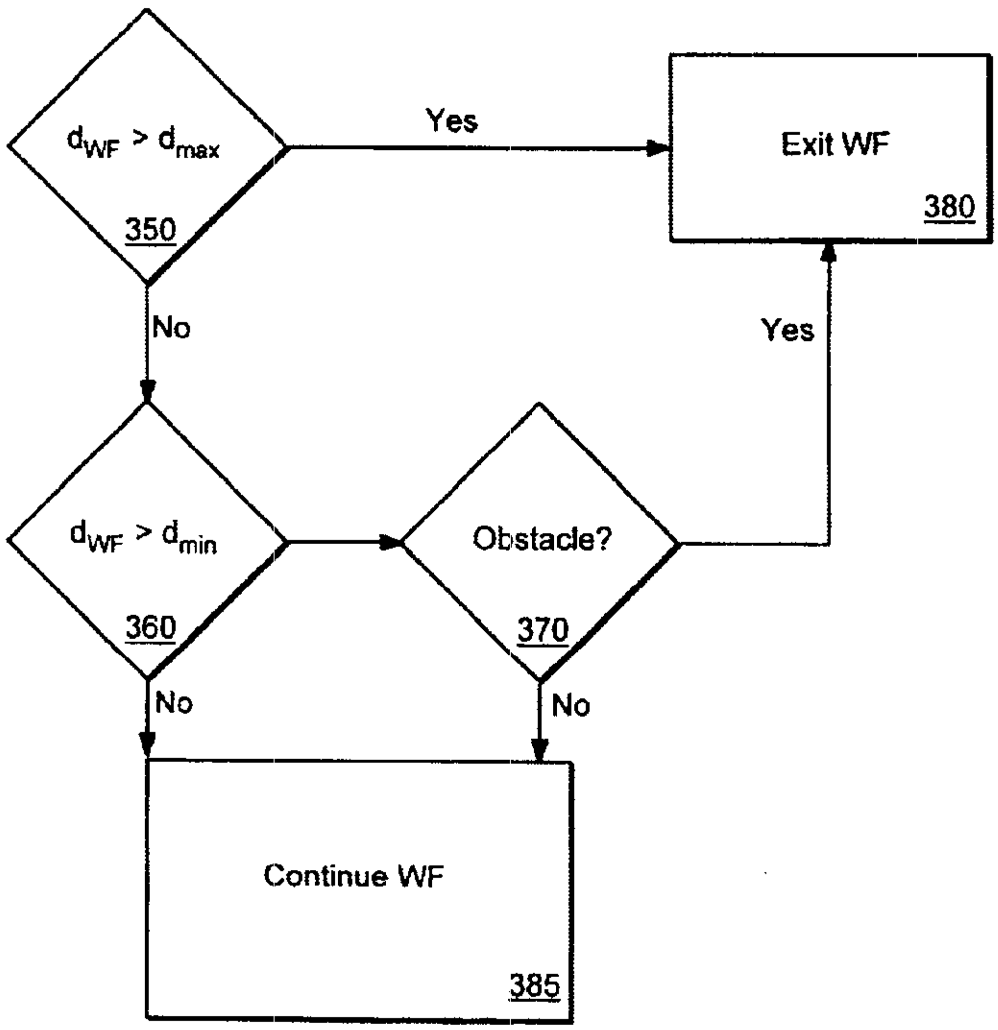

Edge detection begins set value
301
310
e - d
325
Set rating most negative
320
R to NR transit
Yes
No
335
Set rating most positive
330
NR to R transit
Yes
No
340
Decrease absolute value of r

FIG. 9A



$d_{WF} > d_{max}$
350
Yes
Exit WF
380
No
Yes
$d_{WF} > d_{min}$
360
Obstacle?
370
No
No
Continue WF
385

FIG. 9B

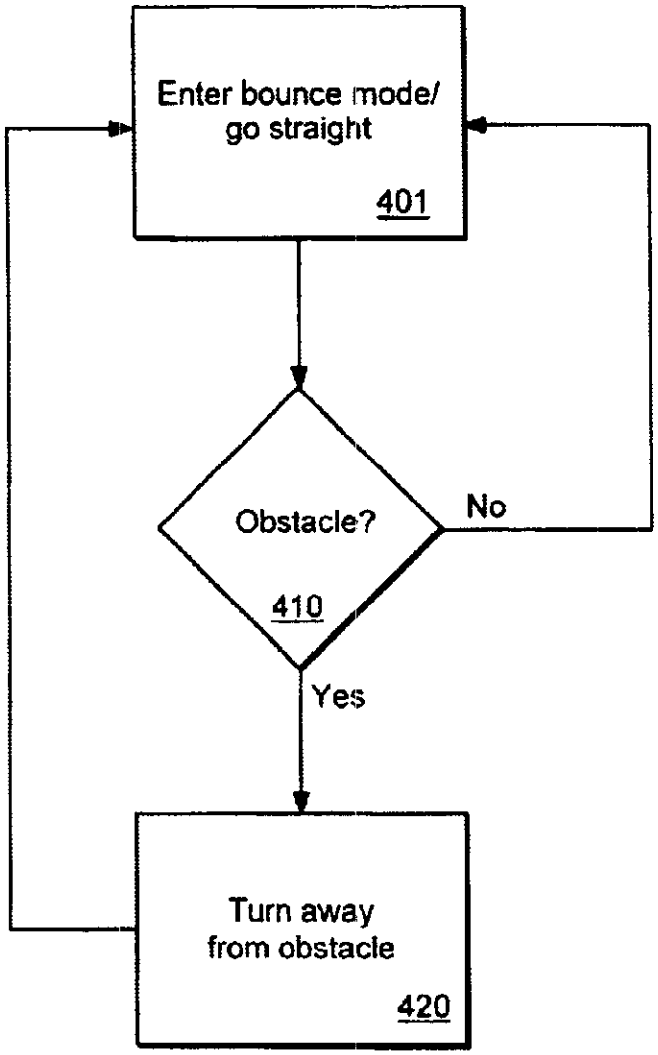

Enter bounce mode/
go straight
401
Obstacle?
410
No
Yes
Turn away
from obstacle
420

FIG. 10

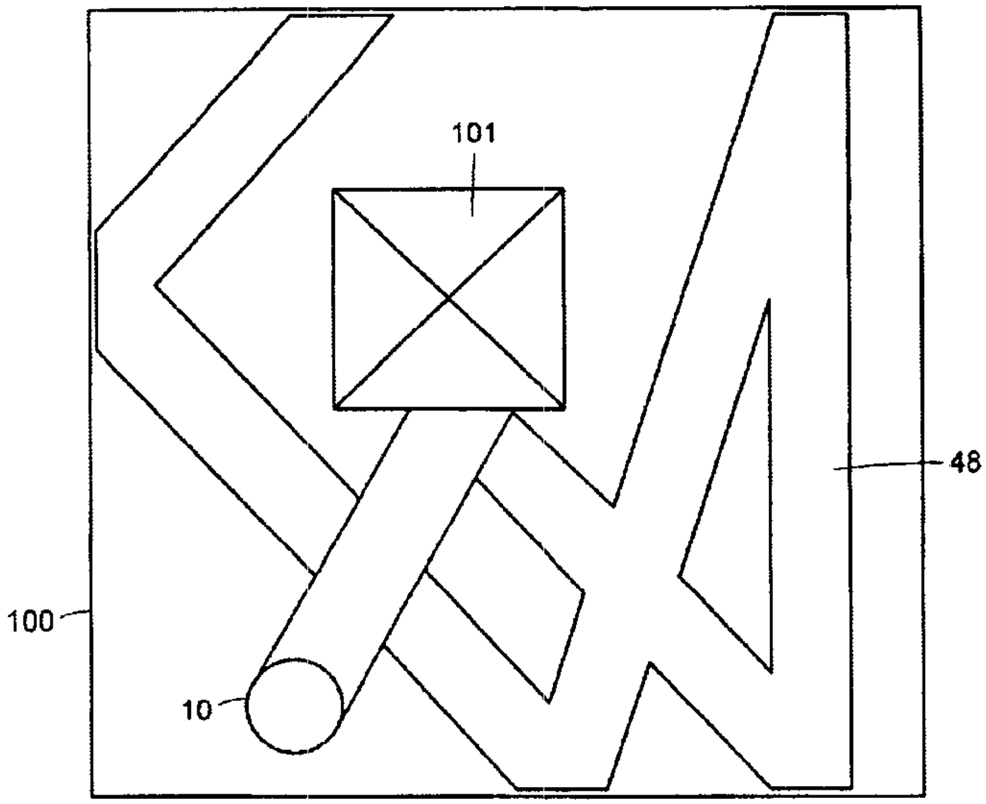


FIG. 11

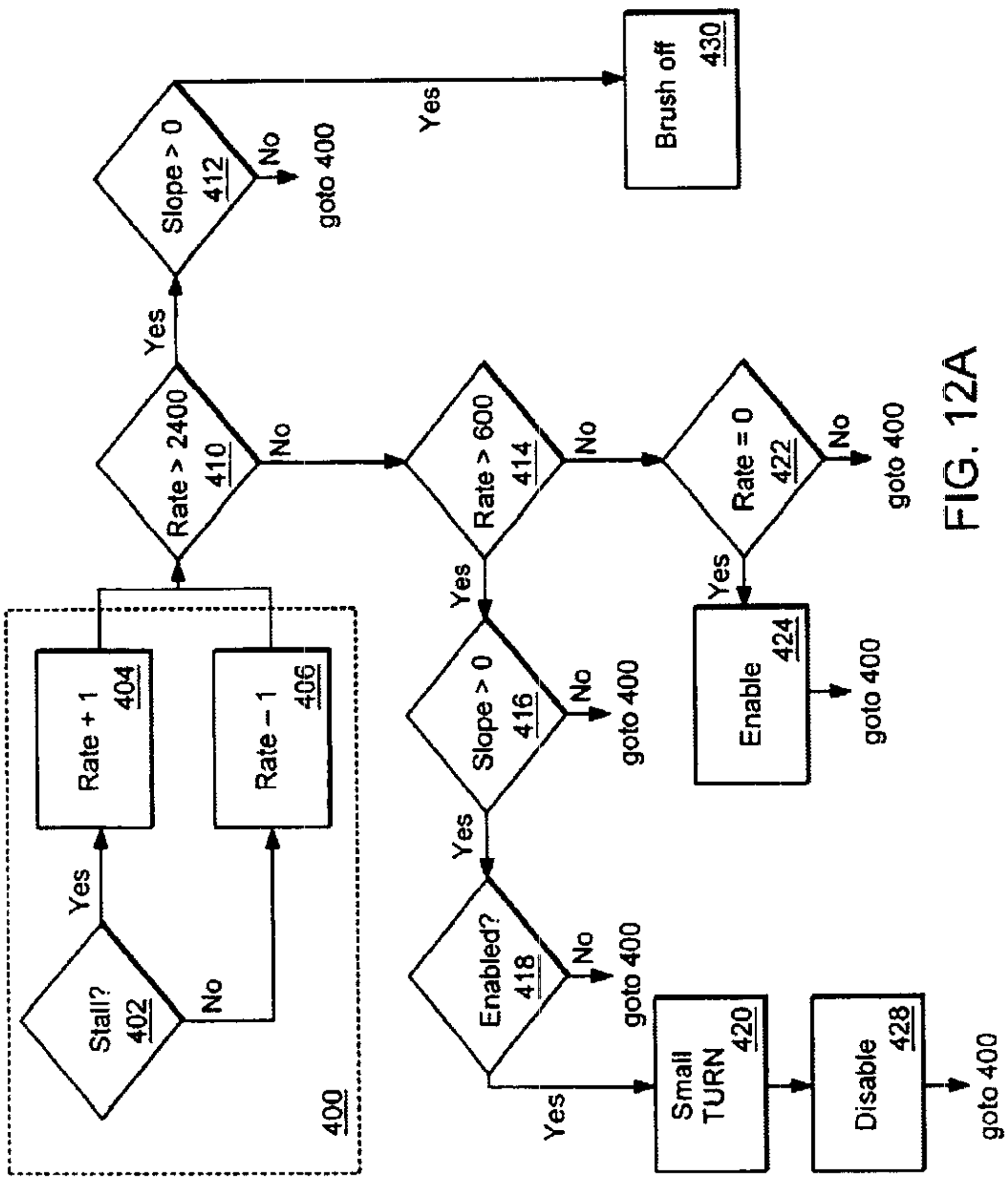

Stall?
402
Yes
No
Rate + 1
404
Rate – 1
406
400
Rate > 2400
410
Yes
No
Slope > 0
412
No
goto 400
Yes
Brush off
430
Rate > 600
414
Yes
No
Slope > 0
416
No
goto 400
Yes
Enabled?
418
No
goto 400
Yes
Small TURN
420
Disable
428
goto 400
Rate = 0
422
No
goto 400
Yes
Enable
424
goto 400

FIG. 12A

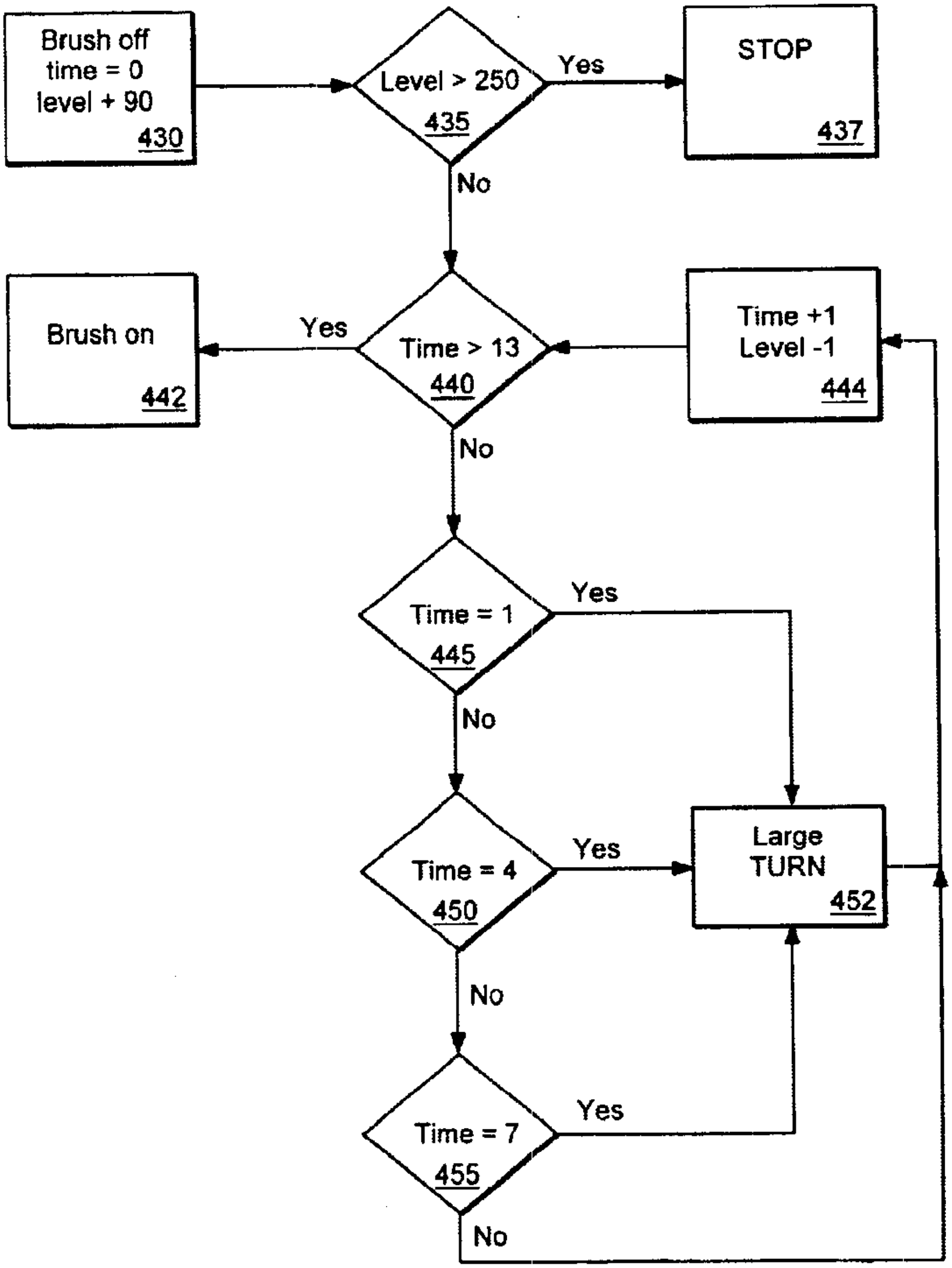

Brush off
time = 0
level + 90
430
Level > 250
435
Yes
STOP
437
No
Brush on
442
Yes
Time > 13
440
Time +1
Level -1
444
No
Time = 1
445
Yes
No
Time = 4
450
Yes
Large
TURN
452
No
Time = 7
455
Yes
No

FIG. 12B

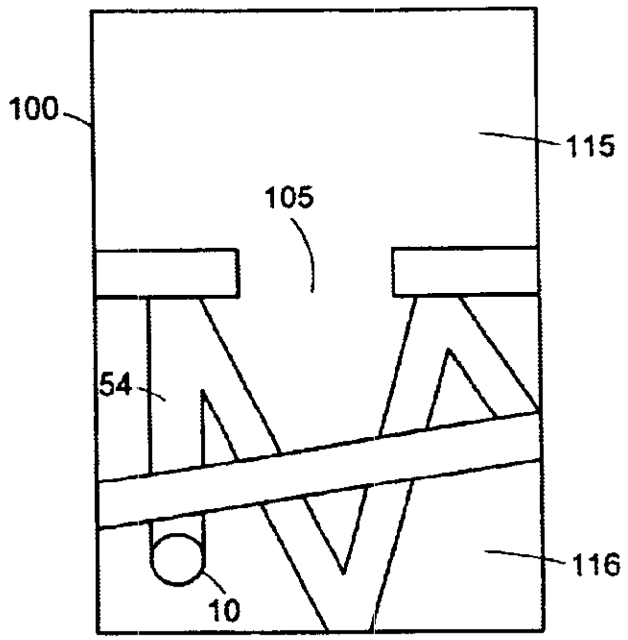


FIG. 13A

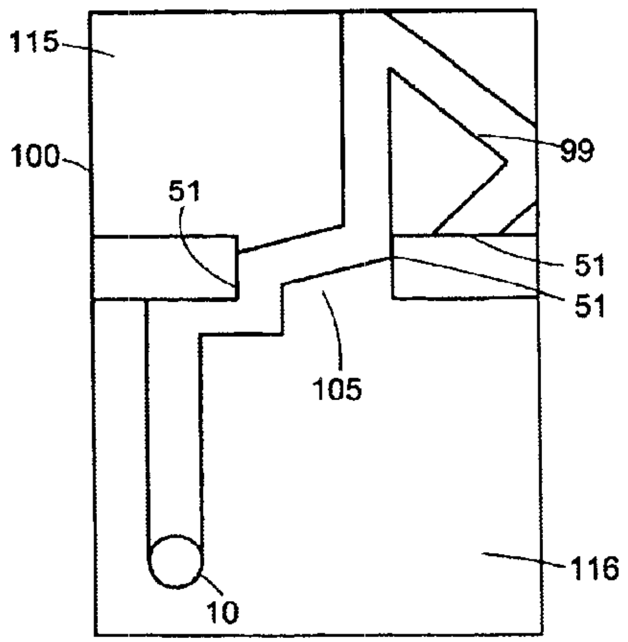


FIG. 13B

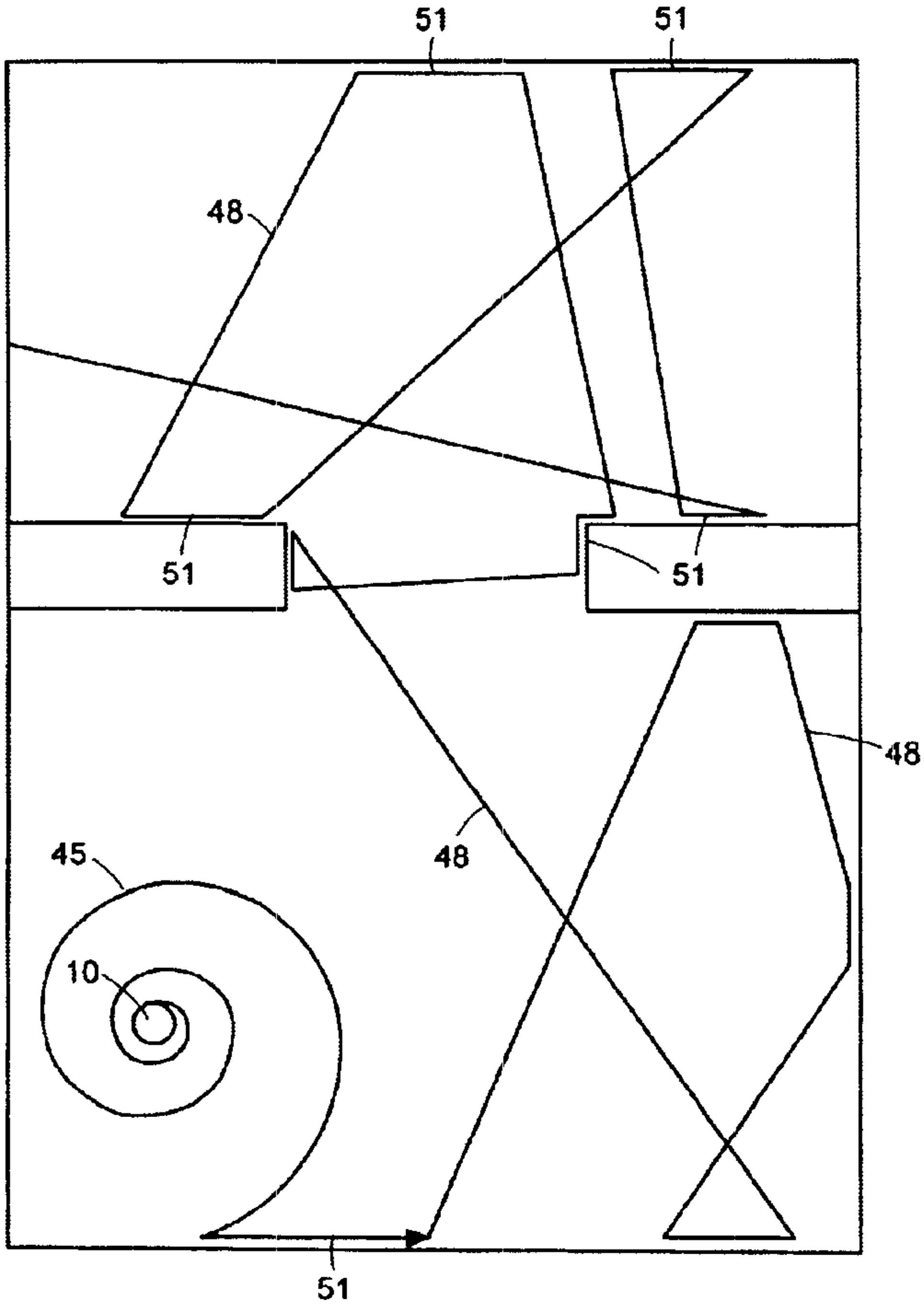


FIG. 14

METHOD AND SYSTEM FOR MULTI-MODE COVERAGE FOR AN AUTONOMOUS ROBOT

This application is entitled to the benefit of U.S. provisional application Ser. No. 60/297,718 filed Jun. 12, 2001.

FIELD OF THE INVENTION

This invention relates generally to autonomous vehicles or robots, and more specifically to methods and mobile robotic devices for covering a specific area as might be required of, or used as, robotic cleaners or lawn mowers.

DESCRIPTION OF PRIOR ART

For purposes of this description, examples will focus on the problems faced in the prior art as related to robotic cleaning (e.g., dusting, buffing, sweeping, scrubbing, dry mopping or vacuuming). The claimed invention, however, is limited only by the claims themselves, and one of skill in the art will recognize the myriad of uses for the present invention beyond indoor, domestic cleaning.

Robotic engineers have long worked on developing an effective method of autonomous cleaning. By way of introduction, the performance of cleaning robots should concentrate on three measures of success: coverage, cleaning rate and perceived effectiveness. Coverage is the percentage of the available space visited by the robot during a fixed cleaning time, and ideally, a robot cleaner would provide 100 percent coverage given an infinite run time. Unfortunately, designs in the prior art often leave portions of the area uncovered regardless of the amount of time the device is allowed to complete its tasks. Failure to achieve complete coverage can result from mechanical limitations--e.g., the size and shape of the robot may prevent it from reaching certain areas--or the robot may become trapped, unable to vary its control to escape. Failure to achieve complete coverage can also result from an inadequate coverage algorithm. The coverage algorithm is the set of instructions used by the robot to control its movement. For the purposes of the present invention, coverage is discussed as a percentage of the available area visited by the robot during a finite cleaning time. Due to mechanical and/or algorithmic limitations, certain areas within the available space may be systematically neglected. Such systematic neglect is a significant limitation in the prior art.

A second measure of a cleaning robot's performance is the cleaning rate given in units of area cleaned per unit time. Cleaning rate refers to the rate at which the area of cleaned floor increases; coverage rate refers to the rate at which the robot covers the floor regardless of whether the floor was previously clean or dirty. If the velocity of the robot is v and the width of the robot's cleaning mechanism (also called work width) is w then the robot's coverage rate is simply wv, but its cleaning rate may be drastically lower.

A robot that moves in a purely randomly fashion in a closed environment has a cleaning rate that decreases relative to the robot's coverage rate as a function of time. This is because the longer the robot operates the more likely it is to revisit already cleaned areas. The optimal design has a cleaning rate equivalent to the coverage rate, thus minimizing unnecessary repeated cleanings of the same spot. In other words, the ratio of cleaning rate to coverage rate is a measure of efficiency and an optimal cleaning rate would mean coverage of the greatest percentage of the designated area with the minimum number of cumulative or redundant passes over an area already cleaned.

A third metric of cleaning robot performance is the perceived effectiveness of the robot. This measure is ignored in the prior art. Deliberate movement and certain patterned movement is favored as users will perceive a robot that contains deliberate movement as more effective.

While coverage, cleaning rate and perceived effectiveness are the performance criteria discussed herein, a preferred embodiment of the present invention also takes into account the ease of use in rooms of a variety of shapes and sizes (containing a variety of unknown obstacles) and the cost of the robotic components. Other design criteria may also influence the design, for example the need for collision avoidance and appropriate response to other hazards.

As described in detail in Jones, Flynn & Seiger, *Mobile Robots: Inspiration to Implementation* second edition, 1999, A K Peters, Ltd., and elsewhere, numerous attempts have been made to build vacuuming and cleaning robots. Each of these robots has faced a similar challenge: how to efficiently cover the designated area given limited energy reserves.

We refer to maximally efficient cleaning, where the cleaning rate equals the coverage rate, as deterministic cleaning. As shown in FIG. **1A**, a robot **1** following a deterministic path moves in such a way as to completely cover the area **2** while avoiding all redundant cleaning. Deterministic cleaning requires that the robot know both where it is and where it has been; this in turn requires a positioning system. Such a positioning system—a positioning system suitably accurate to enable deterministic cleaning might rely on scanning laser rangers, ultrasonic transducers, carrier phase differential GPS, or other methods—can be prohibitively expensive and involve user set-up specific to the particular room geometries. Also, methods that rely on global positioning are typically incapacitated by the failure of any part of the positioning system.

One example of using highly sophisticated (and expensive) sensor technologies to create deterministic cleaning is the RoboScrub device built by Denning Mobile Robotics and Windsor Industries, which used sonar, infrared detectors, bump sensors and high-precision laser navigation. RoboScrub's navigation system required attaching large bar code targets at various positions in the room. The requirement that RoboScrub be able to see at least four targets simultaneously was a significant operational problem. RoboScrub, therefore, was limited to cleaning large open areas.

Another example, RoboKent, a robot built by the Kent Corporation, follows a global positioning strategy similar to RobotScrub. RoboKent dispenses with RobotScrub's more expensive laser positioning system but having done so RoboKent must restrict itself only to areas with a simple rectangular geometry, e.g. long hallways. In these more constrained regions, position correction by sonar ranging measurements is sufficient. Other deterministic cleaning systems are described, for example, in U.S. Pat. No. 4,119,900 (Kremnitz), U.S. Pat. No. 4,700,427 (Knepper), U.S. Pat. No. 5,353,224 (Lee et al, U.S. Pat. No. 5,537,017 (Feiten et al.), U.S. Pat. No. 5,548,511 (Bancroft), 5,650,702 (Azumi).

Because of the limitations and difficulties of deterministic cleaning, some robots have relied on pseudo-deterministic schemes. One method of providing pseudo-deterministic cleaning is an autonomous navigation method known as dead reckoning. Dead reckoning consists of measuring the precise rotation of each robot drive wheel (using for example optical shaft encoders). The robot can then calculate its expected position in the environment given a known

starting point and orientation. One problem with this technique is wheel slippage. If slippage occurs, the encoder on that wheel registers a wheel rotation even though that wheel is not driving the robot relative to the ground. As shown in FIG. 1B, as the robot 1 navigates about the room, these drive wheel slippage errors accumulate making this type of system unreliable for runs of any substantial duration. (The path no longer consists of tightly packed rows, as compared to the deterministic coverage shown in FIG. 1A.) The result of reliance on dead reckoning is intractable systematic neglect; in other words, areas of the floor are not cleaned.

One example of a pseudo-deterministic a system is the Cye robot from Probotics, Inc. Cye depends exclusively on dead reckoning and therefore takes heroic measures to maximize the performance of its dead reckoning system. Cye must begin at a user-installed physical registration spot in a known location where the robot fixes its position and orientation. Cye then keeps track of position as it moves away from that spot. As Cye moves, uncertainty in its position and orientation increase. Cye must make certain to return to a calibration spot before this error grows so large that it will be unlikely to locate a calibration spot. If a calibration spot is moved or blocked or if excessive wheel slippage occurs then Cye can become lost (possibly without realizing that it is lost). Thus Cye is suitable for use only in relatively small benign environments. Other examples of this approach are disclosed in U.S. Pat. No. 5,109,566 (Kobayashi et al.) and U.S. Pat. No. 6,255,793 (Peless et al.).

Another approach to robotic cleaning is purely random motion. As shown in FIG. 1C, in a typical room without obstacles, a random movement algorithm will provide acceptable coverage given significant cleaning time. Compared to a robot with a deterministic algorithm, a random cleaning robot must operate for a longer time to achieve acceptable coverage. To have high confidence that the random-motion robot has cleaned 98% of an obstacle-free room, the random motion robot must run approximately five times as long as a deterministic robot with the same cleaning mechanism moving at the same speed.

The coverage limitations of a random algorithm can be seen in FIG. 1D. An obstacle 5 in the room can create the effect of segmenting the room into a collection of chambers. The coverage over time of a random algorithm robot in such a room is analogous to the time density of gas released in one chamber of a confined volume. Initially, the density of gas is highest in the chamber where it is released and lowest in more distant chambers. Similarly the robot is most likely to thoroughly clean the chamber where it starts, rather than more distant chambers, early in the process. Given enough time a gas reaches equilibrium with equal density in all chambers. Likewise given time, the robot would clean all areas thoroughly. The limitations of practical power supplies, however, usually guarantee that the robot will have insufficient time to clean all areas of a space cluttered with obstacles. We refer to this phenomenon as the robot diffusion problem.

As discussed, the commercially available prior art has not been able to produce an effective coverage algorithm for an area of unknown geometry. As noted above, the prior art either has relied on sophisticated systems of markers or beacons or has limited the utility of the robot to rooms with simple rectangular geometries. Attempts to use pseudo-deterministic control algorithms can leave areas of the space systematically neglected.

OBJECTS AND ADVANTAGES

It is an object of the present invention to provide a system and method to allow a mobile robot to operate in a plurality of modes in order to effectively cover an area.

It is an object of the present invention to provide a mobile robot, with at least one sensor, to operate in a number of modes including spot-coverage, obstacle following and bounce.

It is a further object of the invention to provide a mobile robot that alternates between obstacle following and bounce mode to ensure coverage.

It is an object of the invention to return to spot-coverage after the robot has traveled a pre-determined distance.

It is an object of the invention to provide a mobile robot able to track the average distance between obstacles and use the average distance as an input to alternate between operational modes.

It is yet another object of the invention to optimize the distance the robot travels in an obstacle following mode as a function of the frequency of obstacle following and the work width of the robot, and to provide a minimum and maximum distance for operating in obstacle following mode.

It is an object of a preferred embodiment of the invention to use a control system for a mobile robot with an operational system program able to run a plurality of behaviors and using an arbiter to select which behavior is given control over the robot.

It is still another object of the invention to incorporate various escape programs or behavior to allow the robot to avoid becoming stuck.

Finally, it is an object of the invention to provide one or more methods for controlling a mobile robot to benefit from the various objects and advantages disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

These and further features of the present invention will be apparent with reference to the accompanying drawings, wherein:

FIGS. 1A–D illustrate coverage patterns of various robots in the prior art;

FIG. 2 is a top-view schematic representation of the basic components of a mobile robot used in a preferred embodiment of the invention;

FIG. 3 demonstrates a hardware block diagram of the robot shown in FIG. 2;

FIG. 4A is a diagram showing a method of determining the angle at which the robot encounters an obstacle;

FIG. 4B is a diagram showing the orientation of a preferred embodiment of the robot control system;

FIG. 5 is a schematic representation of the operational modes of the instant invention;

FIG. 6A is a schematic representation of the coverage pattern for a preferred embodiment of SPIRAL behavior;

FIG. 6B is a schematic representation of the coverage pattern for an alternative embodiment of SPIRAL behavior;

FIG. 6C is a schematic representation of the coverage pattern for yet another alternative embodiment of SPIRAL behavior;

FIG. 7 is a flow-chart illustration of the spot-coverage algorithm of a preferred embodiment of the invention;

FIGS. 8A & 8B are schematic representations of the coverage pattern for a preferred embodiment of operation in obstacle following mode;

FIG. 8C is a schematic illustration of the termination of the obstacle following mode when an obstacle is encountered after the mobile robot has traveled a minimum distance.

FIG. 8D is a schematic illustration of the termination of the obstacle following mode after the mobile robot has traveled a maximum distance.

FIG. 9A is a flow-chart illustration of the obstacle following algorithm of a preferred embodiment of the invention;

FIG. 9B is a flow-chart illustration of a preferred algorithm for determining when to exit obstacle following mode.

FIG. 10 is a schematic representation of the coverage pattern for a preferred embodiment of BOUNCE behavior;

FIG. 11 is a flow-chart illustration of the room coverage algorithm of a preferred embodiment of the invention;

FIGS. 12A & 12B are flow-chart illustrations of an exemplary escape behavior;

FIG. 13A is a schematic representation of the coverage pattern of a mobile robot with only a single operational mode;

FIG. 13B is a schematic representation of the coverage pattern for a preferred embodiment of the instant invention using obstacle following and room coverage modes; and

FIG. 14 is a schematic representation of the coverage pattern for a preferred embodiment of the instant invention using spot-coverage, obstacle following and room coverage modes.

DESCRIPTION OF INVENTION

In the present invention, a mobile robot is designed to provide maximum coverage at an effective coverage rate in a room of unknown geometry. In addition, the perceived effectiveness of the robot is enhanced by the inclusion of patterned or deliberate motion. In addition, in a preferred embodiment, effective coverage requires a control system able to prevent the robot from becoming immobilized in an unknown environment.

While the physical structures of mobile robots are known in the art, the components of a preferred, exemplary embodiment of the present invention is described herein. A preferred embodiment of the present invention is a substantially circular robotic sweeper containing certain features. As shown in FIG. 2, for example, the mobile robot **10** of a preferred embodiment includes a chassis **11** supporting mechanical and electrical components. These components include various sensors, including two bump sensors **12** & **13** located in the forward portion of the robot, four cliff sensors **14** located on the robot shell **15**, and a wall following sensor **16** mounted on the robot shell **15**. In other embodiments, as few as one sensor may be used in the robot. One of skill in the art will recognize that the sensor(s) may be of a variety of types including sonar, tactile, electromagnetic, capacitive, etc. Because of cost restraints, a preferred embodiment of the present invention uses bump (tactile) sensors **12** & **13** and reflective IR proximity sensors for the cliff sensors **14** and the wall-following sensor **16**. Details of the IR sensors are described in U.S. patent application U.S. Ser. No. 09/768,773, which disclosure is hereby incorporated by reference.

A preferred embodiment of the robot also contains two wheels **20**, motors **21** for driving the wheels independently, an inexpensive low-end microcontroller **22**, and a rechargeable battery **23** or other power source known in the art. These components are well known in the art and are not discussed in detail herein. The robotic cleaning device **10** further includes one or more cleaning heads **30**. The cleaning head might contain a vacuum cleaner, various brushes, sponges, mops, electrostatic cloths or a combination of

various cleaning elements. The embodiment shown in FIG. 2 also includes a side brush **32**.

As mentioned above, a preferred embodiment of the robotic cleaning device **10** comprises an outer shell **15** defining a dominant side, non-dominant side, and a front portion of the robot **10**. The dominant side of the robot is the side that is kept near or in contact with an object (or obstacle) when the robot cleans the area adjacent to that object (or obstacle). In a preferred embodiment, as shown in FIG. **1**, the dominant side of the robot **10** is the right-hand side relative to the primary direction of travel, although in other embodiments the dominant side may be the left-hand side. In still other embodiments, the robot may be symmetric and thereby does not need a dominant side; however, in a preferred embodiment, a dominant side is chosen for reasons of cost. The primary direction of travel is as shown in FIG. 2 by arrow **40**.

In a preferred embodiment, two bump sensors **12** & **13** are located forward of the wheels **20** relative to the direction of forward movement, shown by arrow **40**. One bump sensor **13** is located on the dominant side of the robot **10** and the other bump sensor **12** is located on the non-dominant side of the robot **10**. When both of these bump sensors **12** & **13** are activated simultaneously, the robot **10** recognizes an obstacle in the front position. In other embodiments, more or fewer individual bump sensors can be used. Likewise, any number of bump sensors can be used to divide the device into any number of radial segments. While in a preferred embodiment the bump sensors **12** & **13** are IR break beam sensors activated by contact between the robot **10** and an obstacle, other types of sensors can be used, including mechanical switches and capacitive sensors that detect the capacitance of objects touching the robot or between two metal plates in the bumper that are compressed on contact. Non-contact sensors, which allow the robot to sense proximity to objects without physically touching the object, such as capacitive sensors or a curtain of IR light, can also be used.

It is useful to have a sensor or sensors that are not only able to tell if a surface has been contacted (or is nearby), but also the angle relative to the robot at which the contact was made. In the case of a preferred embodiment, the robot is able to calculate the time between the activation of the right and left bump switches **12** & **13**, if both are activated. The robot is then able to estimate the angle at which contact was made. In a preferred embodiment shown in FIG. 4A, the bump sensor comprises a single mechanical bumper **44** at the front of the robot with sensors **42** & **43** substantially at the two ends of the bumper that sense the movement of the bumper. When the bumper is compressed, the timing between the sensor events is used to calculate the approximate angle at which the robot contacted the obstacle. When the bumper is compressed from the right side, the right bump sensor detects the bump first, followed by the left bump sensor, due to the compliance of the bumper and the bump detector geometry. This way, the bump angle can be approximated with only two bump sensors.

For example, in FIG. **4A**, bump sensors **42** & **43** are able to divide the forward portion of the robot into six regions (I–VI). When a bump sensor is activated, the robot calculates the time before the other sensor is activated (if at all). For example, when the right bump sensor **43** is activated, the robot measures the time (t) before the left bump sensor **42** is activated. If t is less than t_1, then the robot assumes contact occurred in region IV. If t is greater than or equal to t_1 and less than t_2, then the robot assumes contact was made in region V. If t is greater than or equal to t_2 (including the case

of where the left bump sensor **42** is not activated at all within the time monitored), then the robot assumes the contact occurred in region VI. If the bump sensors are activated simultaneously, the robot assumes the contact was made from straight ahead. This method can be used the divide the bumper into an arbitrarily large number of regions (for greater precision) depending on of the timing used and geometry of the bumper. As an extension, three sensors can be used to calculate the bump angle in three dimensions instead of just two dimensions as in the preceding example.

A preferred embodiment also contains a wall-following or wall-detecting sensor **16** mounted on the dominant side of the robot **10**. In a preferred embodiment, the wall following sensor is an IR sensor composed of an emitter and detector pair collimated so that a finite volume of intersection occurs at the expected position of the wall. This focus point is approximately three inches ahead of the drive wheel in the direction of robot forward motion. The radial range of wall detection is about 0.75 inches.

A preferred embodiment also contains any number of IR cliff sensors **14** that prevent the device from tumbling over stairs or other vertical drops. These cliff sensors are of a construction similar to that of the wall following sensor but directed to observe the floor rather than a wall. As an additional safety and sensing measure, the robot **10** includes a wheel-drop sensor that is able to detect if one or more wheels is unsupported by the floor. This wheel-drop sensor can therefore detect not only cliffs but also various obstacles upon which the robot is able to drive, such as lamps bases, high floor transitions, piles of cords, etc.

Other embodiments may use other known sensors or combinations of sensors.

FIG. **3** shows a hardware block diagram of the controller and robot of a preferred embodiment of the invention. In a preferred embodiment, a Winbond W78XXX series processor is used. It is a microcontroller compatible with the MCS-51 family with 36 general purpose I/O ports, 256 bytes of RAM and 16K of ROM. It is clocked at 40 MHz which is divided down for a processor speed of 3.3 MHz. It has two timers which are used for triggering interrupts used to process sensors and generate output signals as well as a watchdog timer. The lowest bits of the fast timer are also used as approximate random numbers where needed in the behaviors. There are also two external interrupts which are used to capture the encoder inputs from the two drive wheels. The processor also has a UART which is used for testing and debugging the robot control program.

The I/O ports of the microprocessor are connected to the sensors and motors of the robot and are the interface connecting it to the internal state of the robot and its environment. For example, the wheel drop sensors are connected to an input port and the brush motor PWM signal is generated on an output port. The ROM on the microprocessor is used to store the coverage and control program for the robot. This includes the behaviors (discussed below), sensor processing algorithms and signal generation. The RAM is used to store the active state of the robot, such as the average bump distance, run time and distance, and the ID of the behavior in control and its current motor commands.

For purposes of understanding the movement of the robotic device, FIG. **4B** shows the orientation of the robot **10** centered about the x and y axes in a coordinate plane; this coordinate system is attached to the robot. The directional movement of the robot **10** can be understood to be the radius at which the robot **10** will move. In order to rapidly turn away from the wall **100**, the robot **10** should set a positive, small value of r (r_3 in FIG. **4B**); in order to rapidly turn toward the wall, the robot should set a negative, small value of r (r_1 in FIG. **4B**). On the other hand, to make slight turns, the robot should set larger absolute values for r—positive values to move left (i.e. away from the wall, r_4 in FIG. **4B**) and negative values to move right (i.e. toward the wall, (r_2 in FIG. **4B**). This coordinate scheme is used in the examples of control discussed below. The microcontroller **22** controlling differential speed at which the individual wheel motors **21** are run, determines the turning radius.

Also, in certain embodiments, the robot may include one or more user inputs. For example, as shown in FIG. **2**, a preferred embodiment includes three simple buttons **33** that allow the user to input the approximate size of the surface to be covered. In a preferred embodiment, these buttons labeled "small," "medium," and "large" correspond respectively to rooms of 11.1, 20.8 and 27.9 square meters.

As mentioned above, the exemplary robot is a preferred embodiment for practicing the instant invention, and one of skill in the art is able to choose from elements known in the art to design a robot for a particular purpose. Examples of suitable designs include those described in the following U.S. Pat. No. 4,306,329 (Yokoi), U.S. Pat. No. 5,109,566 (Kobayashi et al.), U.S. Pat. No. 5,293,955 (Lee), U.S. Pat. No. 5,369,347 (Yoo), U.S. Pat. No. 5,440,216 (Kim), U.S. Pat. No. 5,534,762 (Kim), U.S. Pat. No. 5,613,261 (Kawakami et al.), U.S. Pat. No. 5,634,237 (Paranjpe), U.S. Pat. No. 5,781,960 (Kilstrom et al.), U.S. Pat. No. 5,787,545 (Colens), U.S. Pat. No. 5,815,880 (Nakanishi), U.S. Pat. No. 5,839,156 (Park et al.), U.S. Pat. No. 5,926,909 (McGee), U.S. Pat. No. 6,038,501 (Kawakami), U.S. Pat. No. 6,076,226 (Reed), all of which are hereby incorporated by reference.

FIG. **5** shows a simple block representation of the various operational modes of a device. In a preferred embodiment, and by way of example only, operational modes may include spot cleaning (where the user or robot designates a specific region for cleaning), edge cleaning, and room cleaning. Each operational mode comprises complex combinations of instructions and/or internal behaviors, discussed below. These complexities, however, are generally hidden from the user. In one embodiment, the user can select the particular operational mode by using an input element, for example, a selector switch or push button. In other preferred embodiments, as described below, the robot is able to autonomously cycle through the operational modes.

The coverage robot of the instant invention uses these various operational modes to effectively cover the area. While one of skill in the art may implement these various operational modes in a variety of known architectures, a preferred embodiment relies on behavior control. Here, behaviors are simply layers of control systems that all run in parallel. The microcontroller **22** then runs a prioritized arbitration scheme to resolve the dominant behavior for a given scenario. A description of behavior control can be found in *Mobile Robots, supra*, the text of which is hereby incorporated by reference.

In other words, in a preferred embodiment, the robot's microprocessor and control software run a number of behaviors simultaneously. Depending on the situation, control of the robot will be given to one or more various behaviors. For purposes of detailing the preferred operation of the present invention, the behaviors will be described as (1) coverage behaviors, (2) escape behaviors or (3) user/safety behaviors. Coverage behaviors are primarily designed to allow the robot to perform its coverage operation in a efficient manner.

Escape behaviors are special behaviors that are given priority when one or more sensor inputs suggest that the robot may not be operating freely. As a convention for this specification, behaviors discussed below are written in all capital letters.

1. Coverage Behaviors

FIGS. **6–14** show the details of each of the preferred operational modes: Spot Coverage, Wall Follow (or Obstacle Follow) and Room Coverage.

Operational Mode: Spot Coverage

Spot coverage or, for example, spot cleaning allows the user to clean an isolated dirty area. The user places the robot **10** on the floor near the center of the area (see reference numeral **40** in FIGS. **6A**, **6B**) that requires cleaning and selects the spot-cleaning operational mode. The robot then moves in such a way that the immediate area within, for example, a defined radius, is brought into contact with the cleaning head **30** or side brush **32** of the robot.

In a preferred embodiment, the method of achieving spot cleaning is a control algorithm providing outward spiral movement, or SPIRAL behavior, as shown in FIG. **6A**. In general, spiral movement is generated by increasing the turning radius as a function of time. In a preferred embodiment, the robot **10** begins its spiral in a counter-clockwise direction, marked in FIG. **6A** by movement line **45**, in order to keep the dominant side on the outward, leading-edge of the spiral. In another embodiment, shown in FIG. **6B**, spiral movement of the robot **10** is generated inward such that the radius of the turns continues to decrease. The inward spiral is shown as movement line **45** in FIG. **6B**. It is not necessary, however, to keep the dominant side of the robot on the outside during spiral motion.

The method of spot cleaning used in a preferred embodiment—outward spiraling—is set forth in FIG. **7**. Once the spiraling is initiated (step **201**) and the value of r is set at its minimum, positive value (which will produce the tightest possible counterclockwise turn), the spiraling behavior recalculates the value of r as a function of θ, where θ represents the angular turning since the initiation of the spiraling behavior (step **210**). By using the equation $r=a\theta$, where a is a constant coefficient, the tightness or desired overlap of the spiral can be controlled. (Note that θ is not normalized to 2π). The value of a can be chosen by the equation

$$a = \frac{d}{2\pi};$$

where d is the distance between two consecutive passes of the spiral. For effective cleaning, a value for d should be chosen that is less than the width of the cleaning mechanism **30**. In a preferred embodiment, a value of d is selected that is between one-half and two-thirds of the width of the cleaning head **30**.

In other embodiments, the robot tracks its total distance traveled in spiral mode. The spiral will deteriorate after some distance, i.e. the centerpoint of the spiral motion will tend to drift over time due to surface dependant wheel slippage and/or inaccuracies in the spiral approximation algorithm and calculation precision. In certain embodiments, therefore, the robot may exit spiral mode after the robot has traveled a specific distance ("maximum spiral distance"), such as 6.3 or 18.5 meters (step **240**). In a preferred embodiment, the robot uses multiple maximum spiral distances depending on whether the robot is performing an initial spiral or a later spiral. If the maximum spiral distance is reached without a bump, the robot gives control to a different behavior, and the robot, for example, then continues to move in a predominately straight line. (In a preferred embodiment, a STRAIGHT LINE behavior is a low priority, default behavior that propels the robot in an approximate straight line at a preset velocity of approximately 0.306 m/s when no other behaviors are active.

In spiral mode, various actions can be taken when an obstacle is encountered. For example, the robot could (a) seek to avoid the obstacle and continue the spiral in the counter-clockwise direction, (b) seek to avoid the obstacle and continue the spiral in the opposite direction (e.g. changing from counter-clockwise to clockwise), or (c) change operational modes. Continuing the spiral in the opposite direction is known as reflective spiraling and is represented in FIG. **6C**, where the robot **10** reverses its movement path **45** when it comes into contact with obstacle **101**. In a preferred embodiment, as detailed in step **220**, the robot **10** exits spot cleaning mode upon the first obstacle encountered by a bump sensor **12** or **13**.

While a preferred embodiment describes a spiral motion for spot coverage, any self-bounded area can be used, including but not limited to regular polygon shapes such as squares, hexagons, ellipses, etc.

Operational Mode: Wall/Obstacle Following

Wall following or, in the case of a cleaning robot, edge cleaning, allows the user to clean only the edges of a room or the edges of objects within a room. The user places the robot **10** on the floor near an edge to be cleaned and selects the edge-cleaning operational mode. The robot **10** then moves in such a way that it follows the edge and cleans all areas brought into contact with the cleaning head **30** of the robot.

The movement of the robot **10** in a room **110** is shown in FIGS. **8A**, **8B**. In FIG. **8A**, the robot **10** is placed along wall **100**, with the robot's dominant side next to the wall. The robot then runs along the wall indefinitely following movement path **46**. Similarly, in FIG. **8B**, the robot **10** is placed in the proximity of an obstacle **101**. The robot then follows the edge of the obstacle **101** indefinitely following movement path **47**.

In a preferred embodiment, in the wall-following mode, the robot uses the wall-following sensor **16** to position itself a set distance from the wall. The robot then proceeds to travel along the perimeter of the wall. As shown in FIGS. **8A** & **8B**, in a preferred embodiment, the robot **10** is not able to distinguish between a wall **100** and another solid obstacle **101**.

The movement of the robot **10** in a room **110** is shown in FIGS. **8A**, **8B**. In FIG. **8A**, the robot **10** is placed along wall **100**, with the robot's dominant side next to the wall. The robot then runs along the wall indefinitely following movement path **46**. Similarly, in FIG. **8B**, the robot **10** is placed in the proximity of an obstacle **101**. The robot then follows the edge of the obstacle **101** indefinitely following movement path **47**.

Once the wall-following operational mode, or WALL FOLLOWING behavior of a preferred embodiment, is initiated (step **301**), the robot first sets its initial value for the steering at r_0. The WALL-FOLLOWING behavior then initiates the emit-detect routine in the wall-follower sensor **16** (step **310**). The existence of a reflection for the IR transmitter portion of the sensor **16** translates into the existence of an object within a predetermined distance from the sensor **16**. The WALL-FOLLOWING behavior then determines whether there has been a transition from a

reflection (object within range) to a non-reflection (object outside of range) (step **320**). If there has been a transition (in other words, the wall is now out of range), the value of r is set to its most negative value and the robot will veer slightly to the right (step **325**). The robot then begins the emit-detect sequence again (step **310**). If there has not been a transition from a reflection to a non-reflection, the wall-following behavior then determines whether there has been a transition from non-reflection to reflection (step **330**). If there has been such a transition, the value of r is set to its most positive value and the robot will veer slightly left (step **335**).

In the absence of either type of transition event, the wall-following behavior reduces the absolute value of r (step **340**) and begins the emit-detect sequence (step **310**) anew. By decreasing the absolute value of r, the robot **10** begins to turn more sharply in whatever direction it is currently heading. In a preferred embodiment, the rate of decreasing the absolute value of r is a constant rate dependant on the distance traveled.

The wall follower mode can be continued for a predetermined or random time, a predetermined or random distance or until some additional criteria are met (e.g. bump sensor is activated, etc.). In one embodiment, the robot continues to follow the wall indefinitely. In a preferred embodiment, as shown in FIGS. **8C** & **8D** wherein reference numeral **46** identifies the movement of the robot, minimum and maximum travel distances are determined, whereby the robot will remain in WALL-FOLLOWING behavior until the robot has either traveled the maximum distance (FIG. **8D**) or traveled at least the minimum distance and encountered an obstacle **101** (FIG. **8C**). This implementation of WALL-FOLLOWING behavior ensures the robot spends an appropriate amount of time in WALL-FOLLOWING behavior as compared to its other operational modes, thereby decreasing systemic neglect and distributing coverage to all areas. By increasing wall following, the robot is able to move in more spaces, but the robot is less efficient at cleaning any one space. In addition, by tending to exit WALL-FOLLOWING behavior after obstacle detection, the robot increases its perceived effectiveness.

FIG. **9B** is a flow-chart illustration showing this embodiment of determining when to exit WALL-FOLLOWING (WF) behavior. The robot first determines the minimum distance to follow the wall (d_{min}) and the maximum distance to follow the wall (d_{max}). While in wall (or obstacle) following mode, the control system tracks the distance the robot has traveled in that mode (d_{WF}). If d_{WF} is greater than d_{max}(step **350**), then the robot exits wall-following mode (step **380**). If, however, d_{WF} is less than d_{max}(step **350**) and d_{WF} is less than d_{min}(step **360**), the robot remains in wall-following mode (step **385**). If d_{WF} is greater than d_{min}(step **360**) and an obstacle is encountered (step **370**), the robot exits wall-following mode (step **380**).

Theoretically, the optimal distance for the robot to travel in WALL-FOLLOWING behavior is a function of room size and configuration and robot size. In a preferred embodiment, the minimum and maximum distances to remain in WALL-FOLLOWING are set based upon the approximate room size, the robots width and a random component, where by the average minimum travel distance is 2 w/p, where w is the width of the work element of the robot and p is the probability that the robot will enter WALL-FOLLOWING behavior in a given interaction with an obstacle. By way of example, in a preferred embodiment, w is approximately between 15 cm and 25 cm, and p is 0.095 (where the robot encounters 6 to 15 obstacles, or an average of 10.5 obstacles, before entering an obstacle following mode). The minimum distance is then set randomly as a distance between approximately 115 cm and 350 cm; the maximum distance is then set randomly as a distance between approximately 170 cm and 520 cm. In certain embodiments the ratio between the minimum distance to the maximum distance is 2:3. For the sake of perceived efficiency, the robot's initial operation in a obstacle following mode can be set to be longer than its later operations in obstacle following mode. In addition, users may place the robot along the longest wall when starting the robot, which improves actual as well as perceived coverage.

The distance that the robot travels in wall following mode can also be set by the robot depending on the number and frequency of objects encountered (as determined by other sensors), which is a measure of room "clutter." If more objects are encountered, the robot would wall follow for a greater distance in order to get into all the areas of the floor. Conversely, if few obstacles are encountered, the robot would wall follow less in order to not over-cover the edges of the space in favor of passes through the center of the space. An initial wall-following distance can also be included to allow the robot to follow the wall a longer or shorter distance during its initial period where the WALL-FOLLOWING behavior has control.

In a preferred embodiment, the robot may also leave wall-following mode if the robot turns more than, for example, 270 degrees and is unable to locate the wall (or object) or if the robot has turned a total of 360 degrees since entering wall-following mode.

In certain embodiments, when the WALL-FOLLOWING behavior is active and there is a bump, the ALIGN behavior becomes active. The ALIGN behavior turns the robot counter-clockwise to align the robot with the wall. The robot always turns a minimum angle to avoid getting the robot getting into cycles of many small turns. After it has turned through its minimum angle, the robot monitors its wall sensor and if it detects a wall and then the wall detection goes away, the robot stops turning. This is because at the end of the wall follower range, the robot is well aligned to start WALL-FOLLOWING. If the robot has not seen its wall detector go on and then off by the time it reaches its maximum angle, it stops anyway. This prevents the robot from turning around in circles when the wall is out of range of its wall sensor. When the most recent bump is within the side 60 degrees of the bumper on the dominant side, the minimum angle is set to 14 degrees and the maximum angle is 19 degrees. Otherwise, if the bump is within 30 degrees of the front of the bumper on the dominant side or on the non-dominant side, the minimum angle is 20 degrees and the maximum angle is 44 degrees. When the ALIGN behavior has completed turning, it cedes control to the WALL-FOLLOWING behavior

Operational Mode: Room Coverage

In a preferred embodiment, the method of performing the room cleaning behavior is a BOUNCE behavior in combination with the STRAIGHT LINE behavior. As shown in FIG. **10**, the robot **10** travels until a bump sensor **12** and/or **13** is activated by contact with an obstacle **101** or a wall **100** (see FIG. **11**). The robot **10** then turns and continues to travel. A sample movement path is shown in FIG. **11** as line **48**.

The algorithm for random bounce behavior is set forth in FIG. **10**. The robot **10** continues its forward movement (step **401**) until a bump sensor **12** and/or **13** is activated (step **410**). The robot **10** then calculates an acceptable range of new directions based on a determination of which bump sensor or sensors have been activated (step **420**). A determination is

then made with some random calculation to choose the new heading within that acceptable range, such as 90 to 270 degrees relative to the object the robot encountered. The angle of the object the robot has bumped is determined as described above using the timing between the right and left bump sensors. The robot then turns to its new headings. In a preferred embodiment, the turn is either clockwise or counterclockwise depending on which direction requires the least movement to achieve the new heading. In other embodiments, the turn is accompanied by movement forward in order to increase the robot's coverage efficiency.

The statistics of the heading choice made by the robot can be distributed uniformly across the allowed headings, i.e. there is an equivalent chance for any heading within the acceptable range. Alternately we can choose statistics based on a Gaussian or other distribution designed to preferentially drive the robot perpendicularly away from a wall.

In other embodiments, the robot could change directions at random or predetermined times and not based upon external sensor activity. Alternatively, the robot could continuously make small angle corrections based on long range sensors to avoid even contacting an object and, thereby cover the surface area with curved paths

In a preferred embodiment, the robot stays in room-cleaning mode until a certain number of bounce interactions are reached, usually between 6 and 13.

2. Escape Behaviors

There are several situations the robot may encounter while trying to cover an area that prevent or impede it from covering all of the area efficiently. A general class of sensors and behaviors called escape behaviors are designed to get the robot out of these situations, or in extreme cases to shut the robot off if it is determined it cannot escape. In order to decide whether to give an escape behavior priority among the various behaviors on the robot, the robot determines the following: (1) is an escape behavior needed; (2) if yes, which escape behavior is warranted?

By way of example, the following situations illustrate situations where an escape behavior is needed for an indoor cleaning robot and an appropriate behavior to run:

(i) Situation 1. The robot detects a situation where it might get stuck—for example, a high spot in a carpet or near a lamp base that acts like a ramp for the robot. The robot performs small "panic" turn behaviors to get out of the situation;

(ii) Situation 2. The robot is physically stuck—for example, the robot is wedged under a couch or against a wall, tangled in cords or carpet tassels, or stuck on a pile of electrical cords with its wheels spinning. The robot performs large panic turn behaviors and turns off relevant motors to escape from the obstruction;

(iii) Situation 3. The robot is in a small, confined area—for example, the robot is between the legs of a chair or in the open area under a dresser, or in a small area created by placing a lamp close to the corner of a room. The robot edge follows using its bumper and/or performs panic turn behaviors to escape from the area; and

(iv) Situation 4. The robot has been stuck and cannot free itself—for example, the robot is in one of the cases in category (ii), above, and has not been able to free itself with any of its panic behaviors. In this case, the robot stops operation and signals to the user for help. This preserves battery life and prevents damage to floors or furniture.

In order to detect the need for each escape situation, various sensors are used. For example:

(i) Situation 1. (a) When the brush or side brush current rise above a threshold, the voltage applied to the relevant motor is reduced. Whenever this is happening, a stall rate variable is increased. When the current is below the threshold, the stall rate is reduced. If the stall level rises above a low threshold and the slope of the rate is positive, the robot performs small panic turn behaviors. It only repeats these small panic turn behaviors when the level has returned to zero and risen to the threshold again. (b) Likewise, there is a wheel drop level variable which is increased when a wheel drop event is detected and is reduced steadily over time. When a wheel drop event is detected and the wheel drop level is above a threshold (meaning there have been several wheel drops recently), the robot performs small or large panic turn behaviors depending on the wheel drop level.

(ii) Situation 2. (a) When the brush stall rate rises above a high threshold and the slope is positive, the robot turns off the brush for 13 seconds and performs large panic turn behaviors at 1, 4, and 7 seconds. At the end of the 13 seconds, the brush is turned back on. (b) When the drive stall rate rises above a medium threshold and the slope is positive, the robot performs large panic turn behaviors continuously. (c) When the drive stall rate rises above a high threshold, the robot turns off all of the motors for 15 seconds. At the end of the 15 seconds, the motors are turned back on. (d) When the bumper of the robot is held in constantly for 5 seconds (as in a side wedging situation), the robot performs a large panic turn behavior. It repeats the panic turn behavior every 5 seconds until the bumper is released. (e) When the robot has gotten no bumps for a distance of 20 feet, it assumes that it might be stuck with its wheels spinning. To free itself, it performs a spiral. If has still not gotten a bump for 10 feet after the end of the spiral, performs a large panic turn behavior. It continues this every 10 feet until it gets a bump.

(iii) Situation 3. (a) When the average distance between bumps falls below a low threshold, the robot performs edge following using its bumper to try to escape from the confined area. (b) When the average distance between bumps falls below a very low threshold, the robot performs large panic turn behaviors to orient it so that it may better be able to escape from the confined area.

(iv) Situation 4. (a) When the brush has stalled and been turned off several times recently and the brush stall rate is high and the slope is positive, the robot shuts off. (b) When the drive has stalled and the motors turned off several times recently and the drive stall rate is high and the slope is positive, the robot shuts off. (c) When any of the wheels are dropped continuously for greater than 2 seconds, the robot shuts off. (d) When many wheel drop events occur in a short time, the robot shuts off. (e) When any of the cliff sensors sense a cliff continuously for 10 seconds, the robot shuts off. (f) When the bump sensor is constantly depressed for a certain amount of time, for example 10 seconds, it is likely that the robot is wedged, and the robot shuts off.

As a descriptive example, FIGS. **12A** & **12B** illustrate the analysis used in a preferred embodiment for identifying the need for an escape behavior relative to a stalled brush motor, as described above in Situations 1, 2 and 4. Each time the brush current exceeds a given limit for the brush motor (step **402**), a rate register is incremented by 1 (step **404**); if no limit is detected, the rate register is decremented by 1 (step **406**). A separate slope register stores the recent values for a recent time period such as 120 cycles. If the rate is above

600 (where 600 corresponds to one second of constant stall) (step **414**) and the slope is positive (step **416**), then the robot will run an escape behavior (step **420**) if the escape behavior is enabled (step **418**). The escape behaviors are disabled after running (step **428**) until the rate has returned to zero (step **422**), re-enabled (step **424**) and risen to 600 again. This is done to avoid the escape behavior being triggered constantly at rates above 600.

If, however, the rate is above 2400 (step **410**) and the slope is positive (step **412**), the robot will run a special set of escape behaviors, shown in FIG. **12B**. In a preferred embodiment, the brush motor will shut off (step **430**), the "level" is incremented by a predetermined amount (**50** to **90**) (step **430**), the stall time is set (step **430**), and a panic behavior (step **452**) is performed at 1 second (step **445**), 4 seconds (step **450**) and 7 seconds (step **455**) since the brush shutoff. The control system then restarts the brush at 13 seconds (steps **440** & **442**). Level is decremented by 1 every second (steps **444**). If level reaches a maximum threshold (step **435**), the robot ceases all operation (step **437**). In addition, the robot may take additional actions when certain stalls are detected, such as limiting the voltage to the motor to prevent damage to the motor.

A preferred embodiment of the robot has four escape behaviors: TURN, EDGE, WHEEL DROP and SLOW.

TURN. The robot turns in place in a random direction, starting at a higher velocity (approximately twice of its normal turning velocity) and decreasing to a lower velocity (approximately one-half of its normal turning velocity). Varying the velocity may aid the robot in escaping from various situations. The angle that the robot should turn can be random or a function of the degree of escape needed or both. In a preferred embodiment, in low panic situations the robot turns anywhere from 45 to 90 degrees, and in high panic situations the robot turns anywhere from 90 to 270 degrees.

EDGE. The robot follows the edge using its bump sensor until (a) the robot turns 60 degrees without a bump or (b) the robot cumulatively has turned more than 170 degrees since the EDGE behavior initiated. The EDGE behavior may be useful if the average bump distance is low (but not so low as to cause a panic behavior). The EDGE behavior allows the robot to fit through the smallest openings physically possible for the robot and so can allow the robot to escape from confined areas.

WHEEL DROP. The robot back drives wheels briefly, then stops them. The back driving of the wheels helps to minimize false positive wheel drops by giving the wheels a small kick in the opposite direction. If the wheel drop is gone within 2 seconds, the robot continues normal operation.

SLOW. If a wheel drop or a cliff detector goes off, the robot slows down to speed of 0.235 m/s (or 77% of its normal speed) for a distance of 0.5 m and then ramps back up to its normal speed.

In addition to the coverage behaviors and the escape behaviors, the robot also might contain additional behaviors related to safety or usability. For example, if a cliff is detected for more than a predetermined amount of time, the robot may shut off. When a cliff is first detected, a cliff avoidance response behavior takes immediate precedence over all other behaviors, rotating the robot away from the cliff until the robot no longer senses the cliff. In a preferred embodiment, the cliff detection event does not cause a change in operational modes. In other embodiments, the robot could use an algorithm similar to the wall-following behavior to allow for cliff following.

The individual operation of the three operational modes has been described above; we now turn to the preferred mode of switching between the various modes.

In order to achieve the optimal coverage and cleaning efficiency, a preferred embodiment uses a control program that gives priority to various coverage behaviors. (Escape behaviors, if needed, are always given a higher priority.) For example, the robot **10** may use the wall following mode for a specified or random time period and then switch operational modes to the room cleaning. By switching between operational modes, the robotic device of the present invention is able to increase coverage, cleaning efficiency and perceived effectiveness.

By way of example, FIGS. **13A** & **13B** show a mobile robot **10** in a "dog bone" shaped environment in which two rooms **115** & **116** of roughly equal dimensions are connected by a narrow passageway **105**. (This example illustrates the robot diffusion problem discussed earlier.) This arrangement is a simplified version of typical domestic environments, where the "dog bone" may be generated by the arrangements of obstacles within the room. In FIG. **13A**, the path of robot **10** is traced as line **54** as robot **10** operates on in random bounce mode. The robot **10** is unable to move from room **116** into **115** during the limited run because the robot's random behavior did not happen to lead the robot through passageway **105**. This method leaves the coverage far less than optimal and the cleaning rate decreased due to the number of times the robot **10** crosses its own path.

FIG. **13B** shows the movement of a preferred embodiment of robot **10**, whereby the robot cycles between BOUNCE and WALL FOLLOWING behaviors. As the robot follows path **99**, each time the robot **10** encounters a wall **100**, the robot follows the wall for a distance equal to twice the robot's diameter. The portions of the path **99** in which the robot **10** operates in wall following mode are labeled **51**. This method provides greatly increased coverage, along with attendant increases in cleaning rate and perceived effectiveness.

Finally, a preferred embodiment of the present invention is detailed in FIG. **14**, in which all three operational modes are used. In a preferred embodiment, the device **10** begins in spiral mode (movement line **45**). If a reflective spiral pattern is used, the device continues in spiral mode until a predetermined or random number of reflective events has occurred. If a standard spiral is used (as shown in FIG. **14**), the device should continue until any bump sensor event. In a preferred embodiment, the device immediately enters wall following mode after the triggering event.

In a preferred embodiment, the device then switches between wall following mode (movement lines **51**) and random bounce modes (movement lines **48**) based on bump sensor events or the completion of the wall following algorithm. In one embodiment, the device does not return to spiral mode; in other embodiments, however, the device can enter spiral mode based on a predetermined or random event.

In a preferred embodiment, the robot keeps a record of the average distance traveled between bumps. The robot then calculates an average bump distance (ABD) using the following formula: (¾×ABD)+(¼×most recent distance between bumps). If the ABD is a above a predetermined threshold, the robot will again give priority to the SPIRAL behavior. In still other embodiments, the robot may have a minimum number of bump events before the SPIRAL behavior will again be given priority. In other embodiments, the robot may enter SPIRAL behavior if it travels a maximum distance, for example 20 feet, without a bump event.

In addition, the robot can also have conditions upon which to stop all operations. For example, for a given room size, which can be manually selected, a minimum and maximum

run time are set and a minimum total distance is selected. When the minimum time and the minimum distance have been reached the robot shuts off. Likewise, if the maximum time has been reached, the robot shuts off.

Of course, a manual control for selecting between operational modes can also be used. For example, a remote control could be used to change or influence operational modes or behaviors. Likewise, a switch mounted on the shell itself could be used to set the operation mode or the switching between modes. For instance, a switch could be used to set the level of clutter in a room to allow the robot a more appropriate coverage algorithm with limited sensing ability.

One of skill in the art will recognize that portions of the instant invention can be used in autonomous vehicles for a variety of purposes besides cleaning. The scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given.

We claim:

1. A mobile robot comprising:

(a) means for moving the robot over a surface;

(b) an obstacle detection sensor;

(c) and a control system operatively connected to said obstacle detection sensor and said means for moving;

(d) said control system configured to operate the robot in a plurality of operational modes and to select from among the plurality of modes in real time in response to signals generated by the obstacle detection sensor, said plurality of operational modes comprising: a spot-coverage mode whereby the robot operates in an isolated area, an obstacle following mode whereby said robot travels adjacent to an obstacle, and a bounce mode whereby the robot travels substantially in a direction away from an obstacle after encountering the obstacle, and wherein, when in the obstacle following mode, the robot travels adjacent to an obstacle for a distance at least twice the work width of the robot.

2. A mobile robot according to claim **1** in which said control system is configured to operate first in said spot-coverage mode, then alternate operation between said obstacle following mode and said bounce mode.

3. A mobile robot according to claim **2** in which said spot-coverage mode comprises substantially spiral movement.

4. A mobile robot according to claim **2** in which the control system is configured to return to said spot-coverage mode after a predetermined traveling distance.

5. A mobile robot according to claim **2** in which the control system is configured to return to said spot-coverage mode after a predetermined elapsed time.

6. A mobile robot according to claim **2** in which the control system is configured to return to said spot-coverage mode if the average distance between obstacle interactions is above a predetermined threshold.

7. A mobile robot according to claim **1**, whereby said obstacle detection sensor comprises a tactile sensor.

8. A mobile robot according to claim **7**, whereby said obstacle detection sensor further comprises an IR sensor.

9. The mobile robot according to claim **1**, whereby said obstacle following mode comprises alternating between decreasing the turning radius of the robot as a function of distance traveled such that the robot turns towards the obstacle until the obstacle detection sensor detects the obstacle, and decreasing the turning radius of the robot as a function of distance traveled such that the robot turns away from the obstacle until the obstacle detection system no longer detects the obstacle.

10. The mobile robot according to claim **1**, whereby the robot operates in said obstacle following mode for a distance greater than twice the work width of the robot and less than approximately ten times the work width of the robot.

11. The mobile robot according to claim **10**, whereby the robot operates in said obstacle following mode for a distance greater than twice the work width of the robot and less than five times the work width of the robot.

12. The mobile robot according to claim **1**, further comprising a means for manually selecting an operational mode.

13. A mobile robot comprising:

(a) means for moving the robot over a surface;

(b) an obstacle detection sensor;

(c) and a control system operatively connected to said obstacle detection sensor and said means for moving;

(d) said control system configured to operate the robot in a plurality of operational modes and to select from among the plurality of modes in real time in response to signals generated by the obstacle detection sensor, said plurality of operational modes comprising: an obstacle following mode whereby said robot travels adjacent to an obstacle for a distance at least twice the work width of the robot and a bounce mode whereby the robot travels substantially in a direction away from an obstacle after encountering the obstacle;

(e) whereby said control system is configured to alternate into said obstacle following mode after a predetermined number of sensor interactions.

14. A mobile robot according to claim **13**, wherein said predetermined number of sensor interactions is randomly determined.

15. A mobile robot according to claim **13**, wherein said predetermined number of sensor interactions is between approximately 5 and approximately 15.

16. A mobile robot according to claim **13**, wherein said control system is configured to alternate into said bounce mode after the robot travels a predetermined distance in said obstacle following mode.

17. A mobile robot according to claim **13**, wherein said control system is configured to alternate into said bounce mode upon either the robot has traveled a maximum distance or the robot has traveled a minimum distance and an obstacle has been encountered.

18. A mobile robot according to claim **17**, wherein said minimum distance is at least 115 cm.

19. A mobile robot according to claim **18**, wherein said maximum distance is less than 520 cm.

20. A mobile robot according to claim **13**, wherein the control system alternates operational modes based on the distance traveled by said robot.

21. A mobile robot comprising:

(a) means for moving the robot over a surface;

(b) an obstacle detection sensor;

(c) a control system operatively connected to said obstacle detection sensor and said robot moving means; and wherein

(d) said control system is configured to operate the robot in a plurality of operational modes, said plurality of operational modes including an obstacle following mode wherein the robot travels adjacent to an obstacle, and a bounce mode wherein the robot travels substantially in a direction away from an obstacle after encountering the obstacle;

(e) said control system being further configured to alternate into said obstacle following mode after a predetermined number of sensor interactions; and

(f) a means for determining a level of clutter associated with the surface over which the robot moves.

22. A mobile robot according to claim 21, wherein said means for determining the level of clutter comprises tracking the number of interactions with obstacles over time.

23. A mobile robot according to claim 22, further comprising a means for imputing the approximate area of the surface, wherein said means for determining the level of clutter further relates to the approximate area of the surface.

24. A mobile robot according to claim 22, wherein the level of clutter is correlated to the frequency at which the controller alternates operational modes.

25. A mobile robot according to claim 21, wherein the level of clutter is positively correlated to a minimum obstacle following distance.

26. A mobile robot comprising:

(a) means for moving the robot over a surface;

(b) an obstacle detection sensor; and

(c) a control system operatively connected to said obstacle detection sensor and said robot moving means; and wherein

(d) said control system is configured to operate the robot in a plurality of operational modes, said plurality of operational modes including an obstacle following mode wherein the robot travels adjacent to an obstacle, and a bounce mode wherein the robot travels substantially in a direction away from an obstacle after encountering the obstacle;

(e) said control system being further configured to alternate into said obstacle following mode after a predetermined number of sensor interactions; and further

(f) wherein the control system alternates between said operational modes based upon a lack of sensor input.

27. A mobile robot according to claim 1, wherein said control system further comprises memory wherein an operational system program is stored, said operational system program comprising a plurality of behaviors and an arbiter to select which behavior is given control over the means for moving.

28. A mobile robot according to claim 27, further comprising an escape behavior.

29. A mobile robot according to claim 28, wherein said obstacle detection sensor comprises a tactile sensor, and wherein said escape behavior comprises operating in said obstacle following mode.

30. A mobile robot according to claim 28, wherein said escape behavior is triggered by the rate of a motor stall event.

31. A mobile robot according to claim 30, wherein said escape behavior is triggered by an increase in said rate of a motor stall event.

32. A mobile robot according to claim 28, wherein said escape behavior is triggered by the duration of sensor input.

33. A mobile robot according to claim 28, wherein said escape behavior comprises shutting off the robot.

34. A mobile robot according to claim 28, wherein said escape behavior is triggered by a lack of sensor input.

35. A mobile robot according to claim 13, further comprising a cliff detector, whereby said control system is configured to reduce the robot's velocity upon detection of a cliff.

36. A mobile robot comprising:

(a) means for moving the robot over a surface;

(b) an obstacle detection sensor;

(c) and a control system operatively connected to said obstacle detection sensor and said means for moving;

(d) said control system configured to operate the robot in a plurality of modes, said plurality of modes comprising: an obstacle following mode whereby said robot travels adjacent to an obstacle, and a bounce mode whereby the robot travels substantially in a direction away from an obstacle after encountering the obstacle;

(e) whereby said control system is configured to alternate into said obstacle following mode after a predetermined number of sensor interactions, and further comprising:

(f) a wheel drop sensor, whereby said robot utilizes the rate of wheel drop sensor events as input to said control system.

37. A method of controlling a mobile-robot equipped with a sensor for detecting an obstacle, said method comprising the steps of:

a. moving in a spiral running motion;

b. discontinuing said spiral running motion after the earlier of sensing an obstacle or traveling a predetermined distance;

c. running in a substantially forward direction until an obstacle is detected;

d. turning and running along the detected obstacle for a distance at least twice the work width of the robot;

e. turning away from the detected obstacle and running in a substantially forward direction; and

f. thereafter repeating said step of running along a detected obstacle and said step of turning away from the detected obstacle,

wherein changes in movement are selected in real time in response to any of calculated distance or signals generated by the sensor.

38. The mobile-robot steering method according to claim 37, further comprising the step of repeating the spiral running motion after a predetermined number of sensor events.

39. The mobile-robot steering method according to claim 37, whereby the robot runs along said obstacle for at least a minimum distance but less than a maximum distance.

40. The mobile-robot steering method according to claim 39, whereby said obstacle sensor comprises an IR sensor able to detect said boundary.

41. The mobile-robot steering method according to claim 40, whereby said obstacle sensor further comprises a tactile sensor.

42. A mobile robot comprising:

(a) means for moving the robot over a surface;

(b) an obstacle detection sensor;

(c) a cliff sensor; and

(d) a control system operatively connected to said obstacle detection sensor, said cliff sensor, and said means for moving;

(e) said control system configured to operate the robot in a plurality of operational modes, said plurality of operational modes comprising: a spot-coverage mode whereby the robot operates in an isolated area, an obstacle following mode whereby said robot travels adjacent to an obstacle for a distance at least twice the work width of the robot, and a bounce mode whereby the robot travels substantially in a direction away from an obstacle after encountering the obstacle.

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(54) **AUTONOMOUS FLOOR-CLEANING ROBOT**

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(52) **U.S. Cl.** **15/319**; 700/245
(58) **Field of Search** 15/319, 339; 700/245

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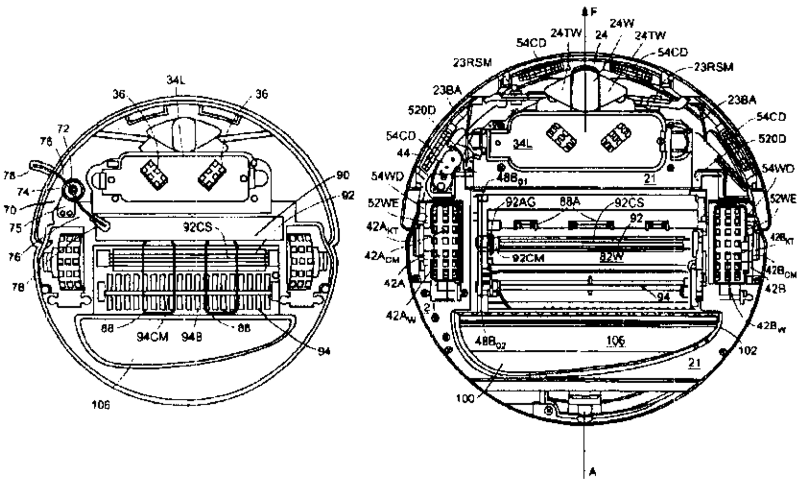
(57) **ABSTRACT**

An autonomous floor-cleaning robot comprises a self-adjusting cleaning head subsystem that includes a dual-stage brush assembly having counter-rotating, asymmetric brushes and an adjacent, but independent, vacuum assembly such that the cleaning capability and efficiency of the self-adjustable cleaning head subsystem is optimized while concomitantly minimizing the power requirements thereof. The autonomous floor-cleaning robot further includes a side brush assembly for directing particulates outside the envelope of the robot into the self-adjusting cleaning head subsystem.

6 Claims, 13 Drawing Sheets



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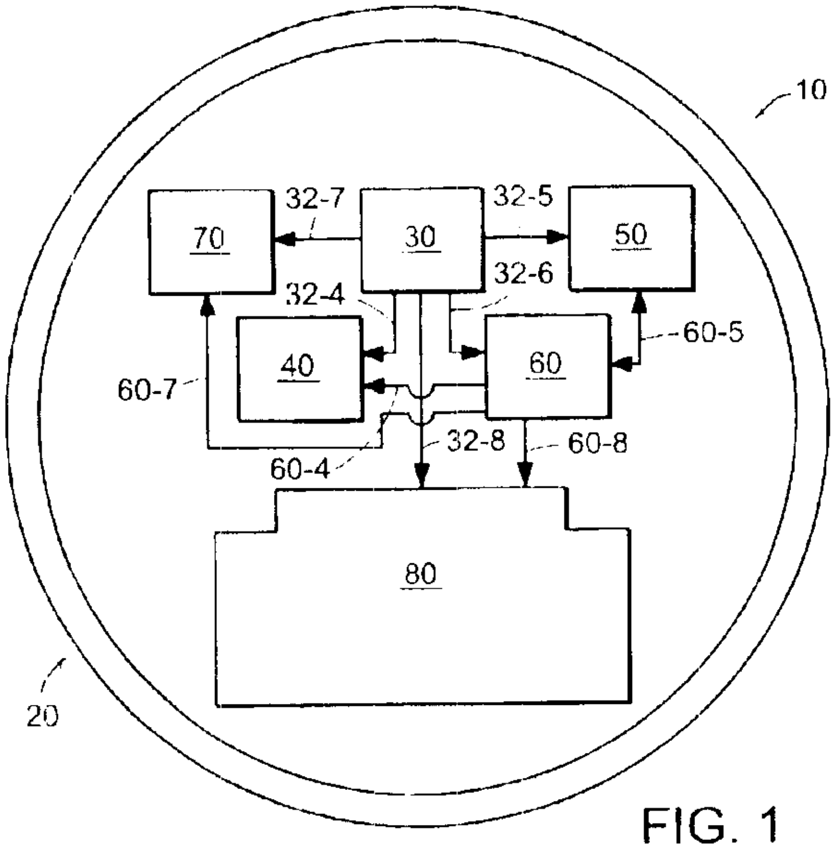
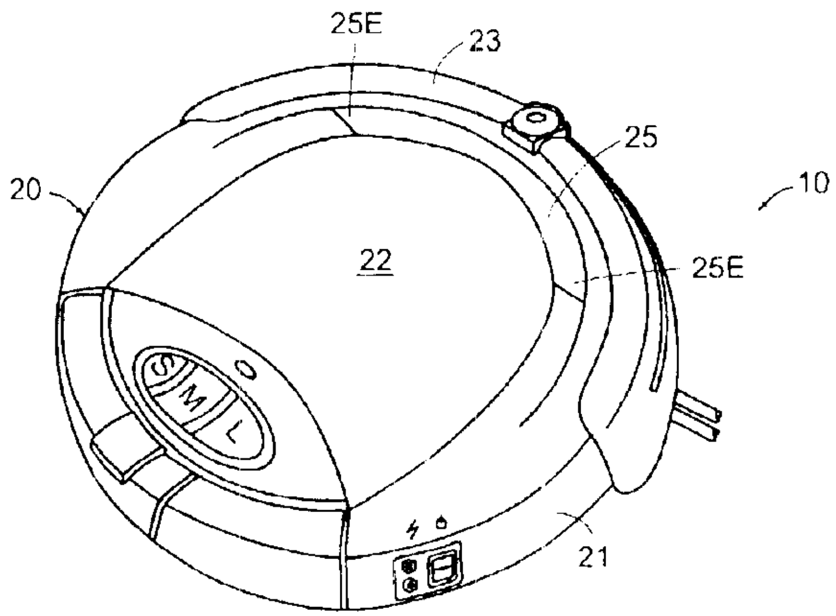


10
70
30
50
32-7
32-5
32-6
32-4
40
60
60-5
60-7
60-4
32-8
60-8
80
20

FIG. 1



25E
23
25
20
10
22
25E
S
M
L
21

FIG. 2

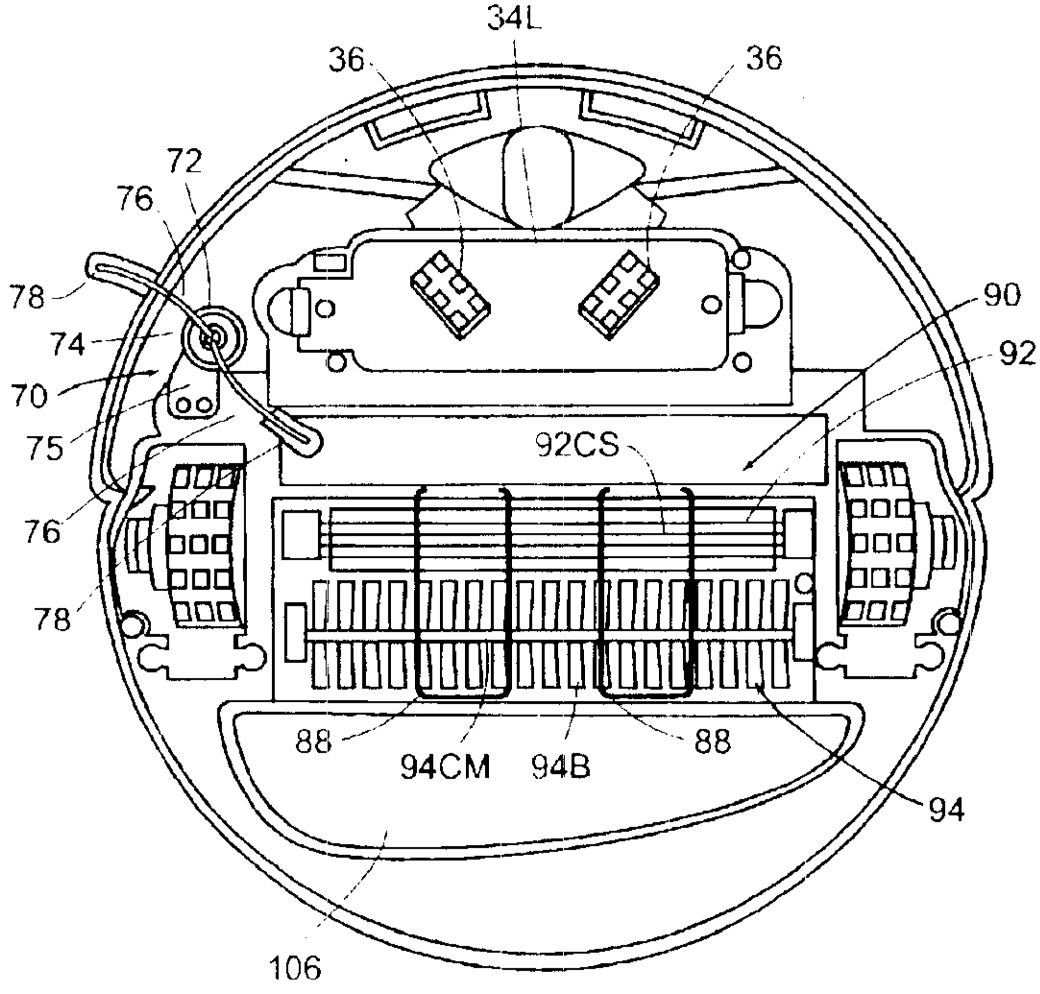
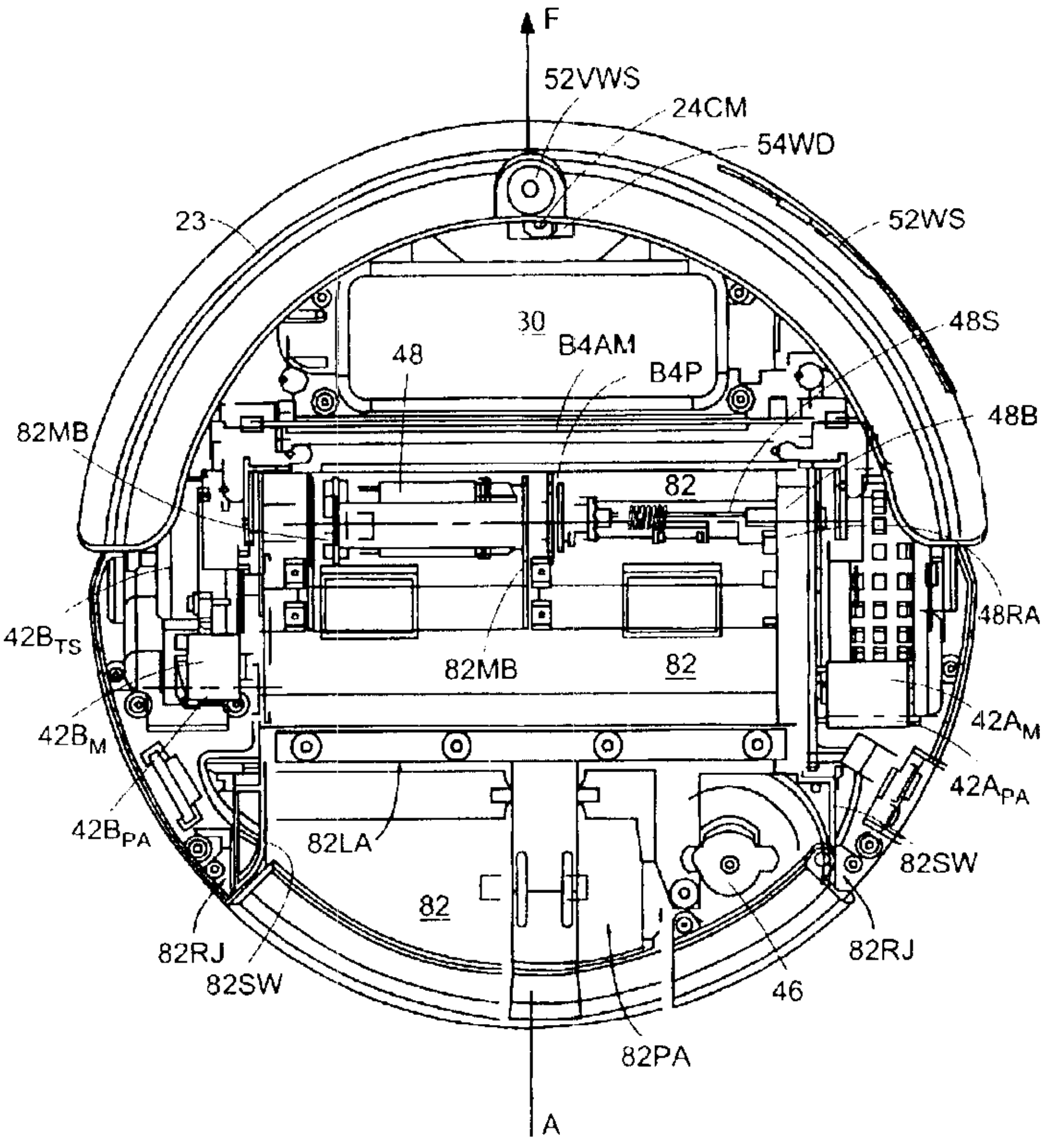


FIG. 2A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52WS
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B4P
48S
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48B
82
48RA
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82MB
82
$42A_M$
$42B_M$
$42A_{PA}$
$42B_{PA}$
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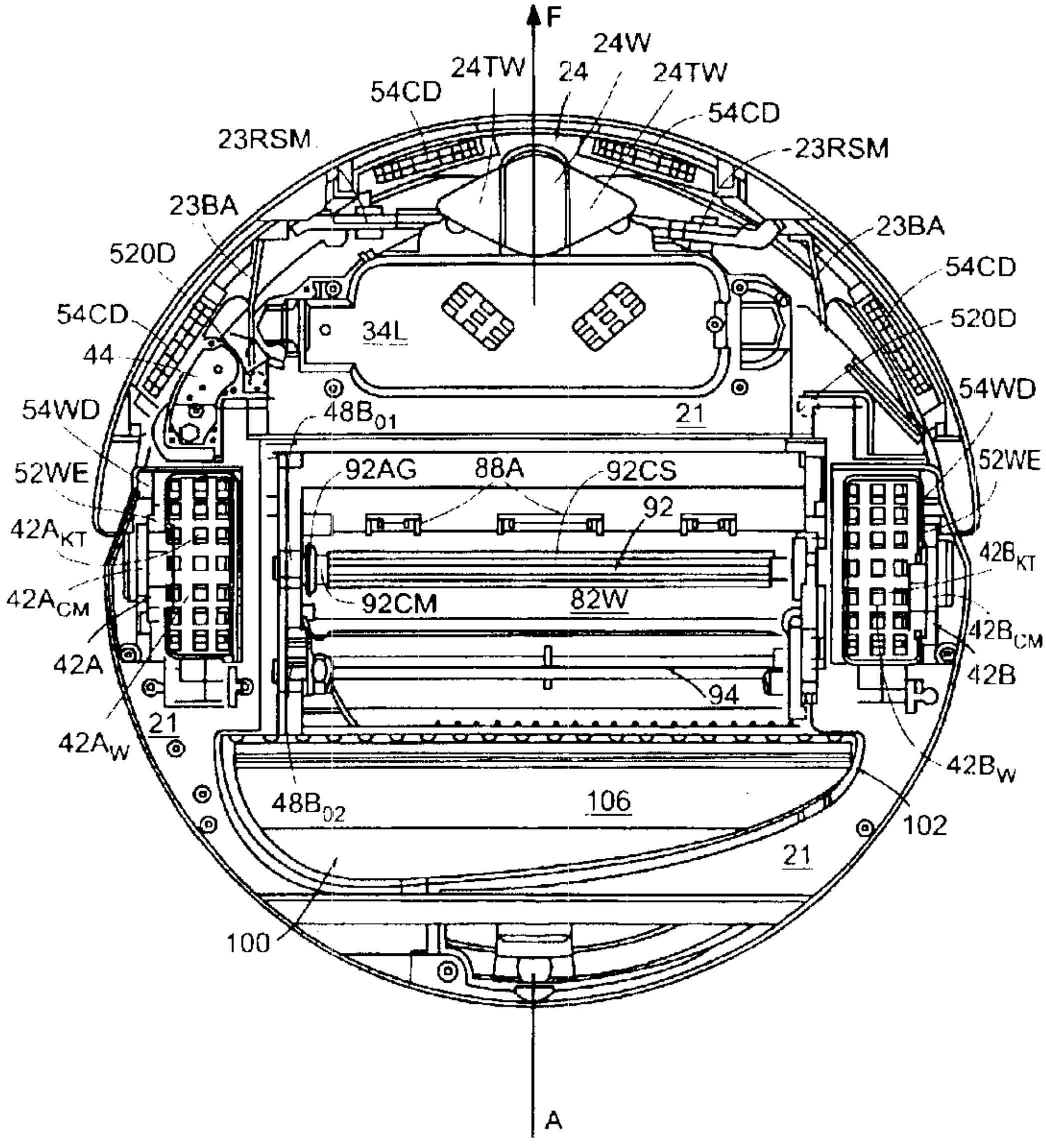
82SW
82
82RJ
82RJ
82SW
46
82PA
A

FIG. 3A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23RSM
23BA
23BA
520D
54CD
54CD
520D
44
34L
54WD
48B01
21
54WD
52WE
92AG
88A
92CS
52WE
92
42AKT
42BKT
42ACM
92CM
82W
42BCM
42A
42B
94
21
42AW
42BW
48B02
106
102
21
100
A

FIG. 3B

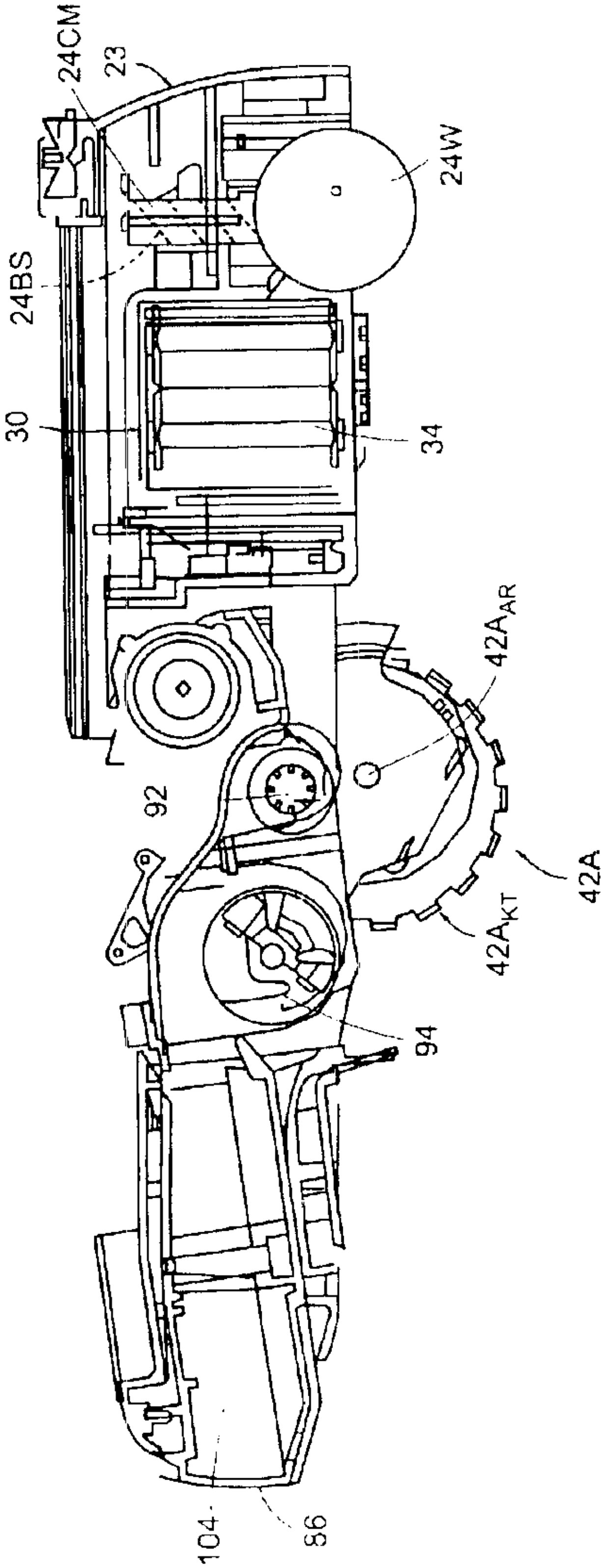


FIG. 3C

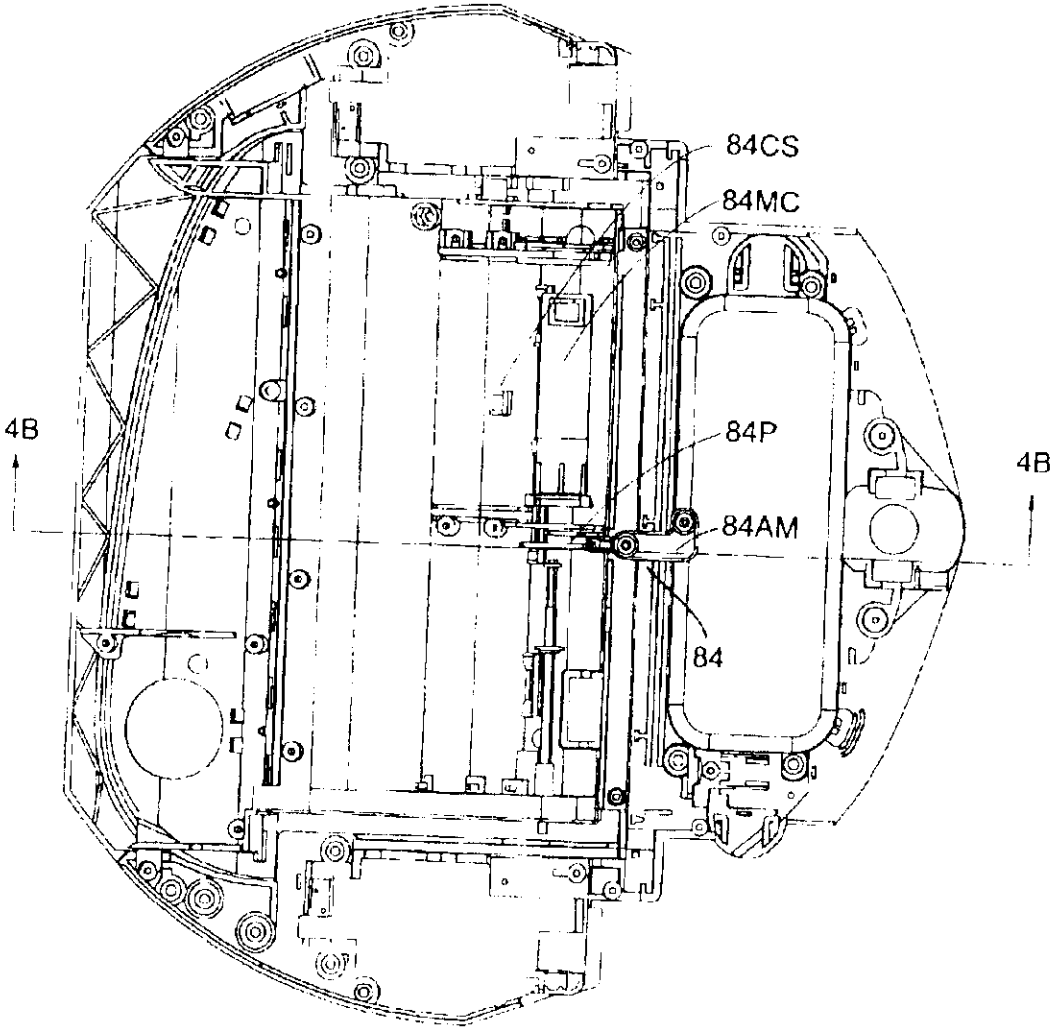


FIG. 4A

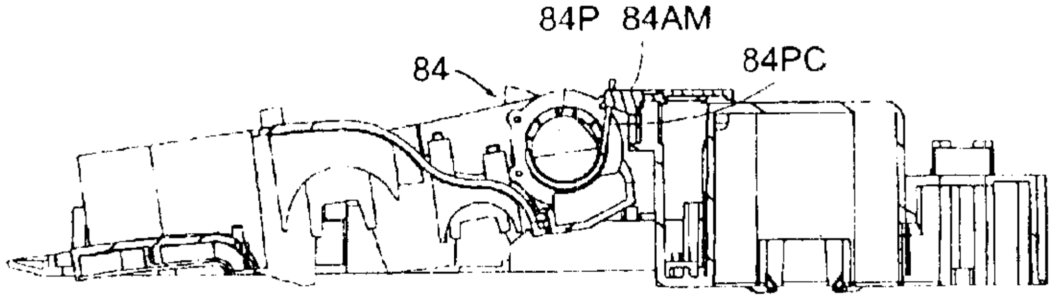


FIG. 4B

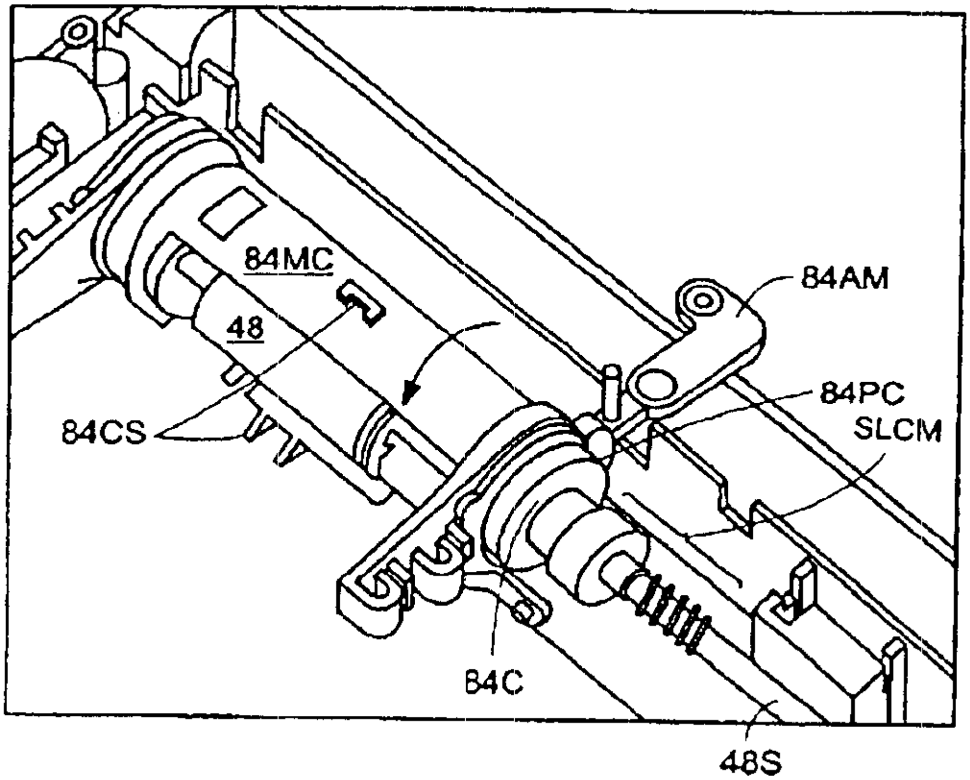


FIG. 4C

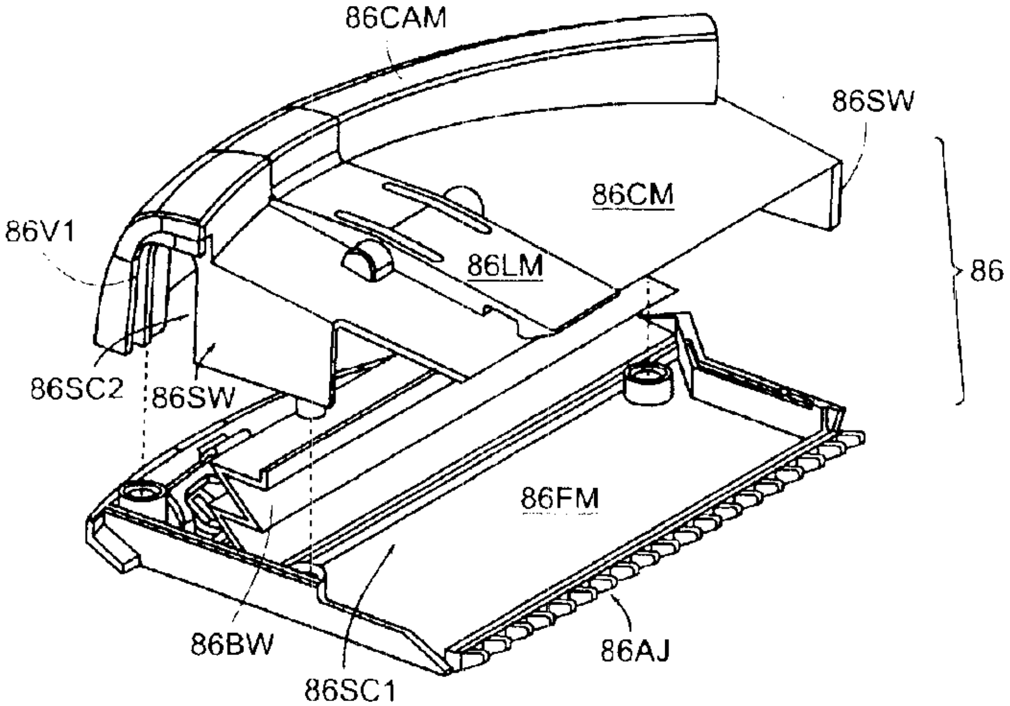


FIG. 5A

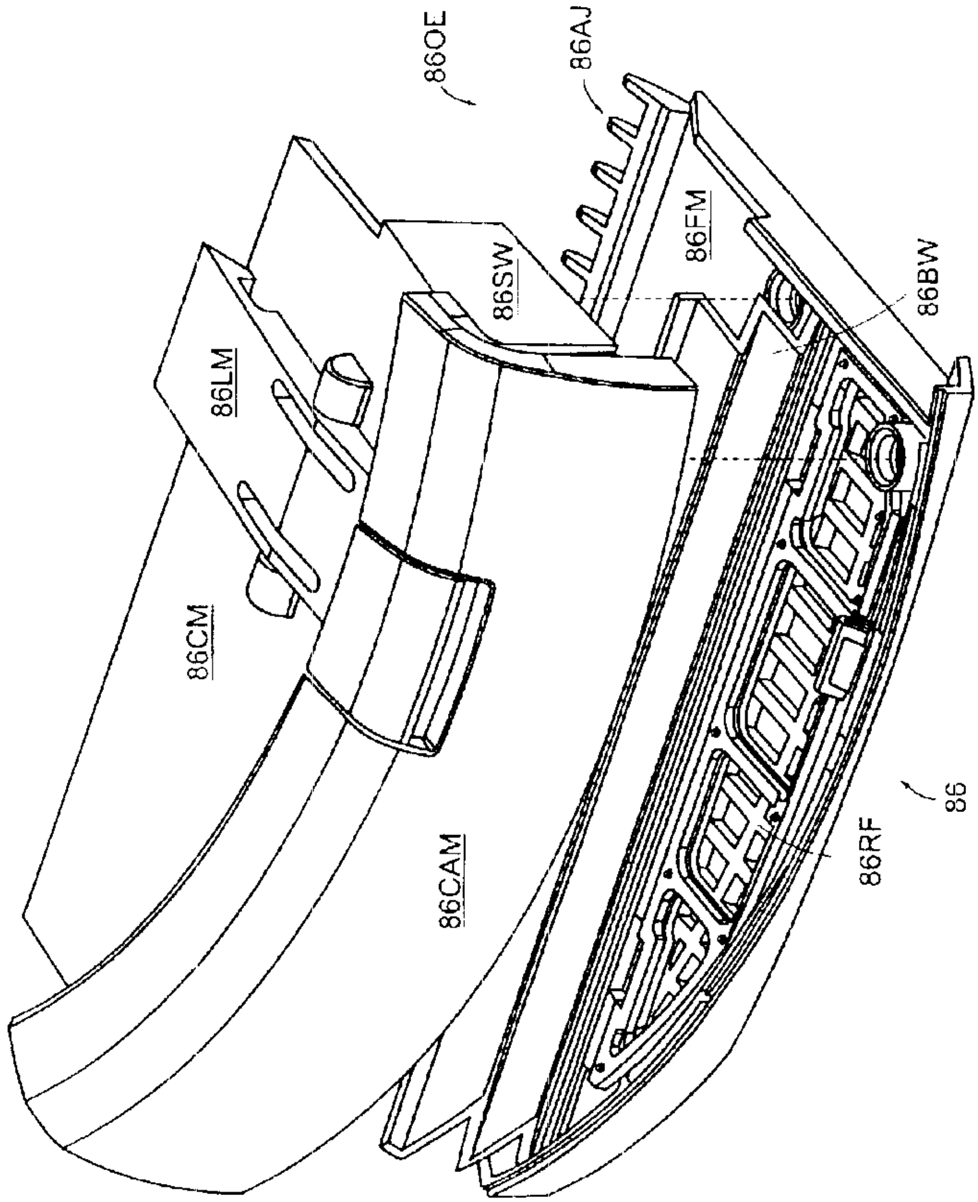


FIG. 5B

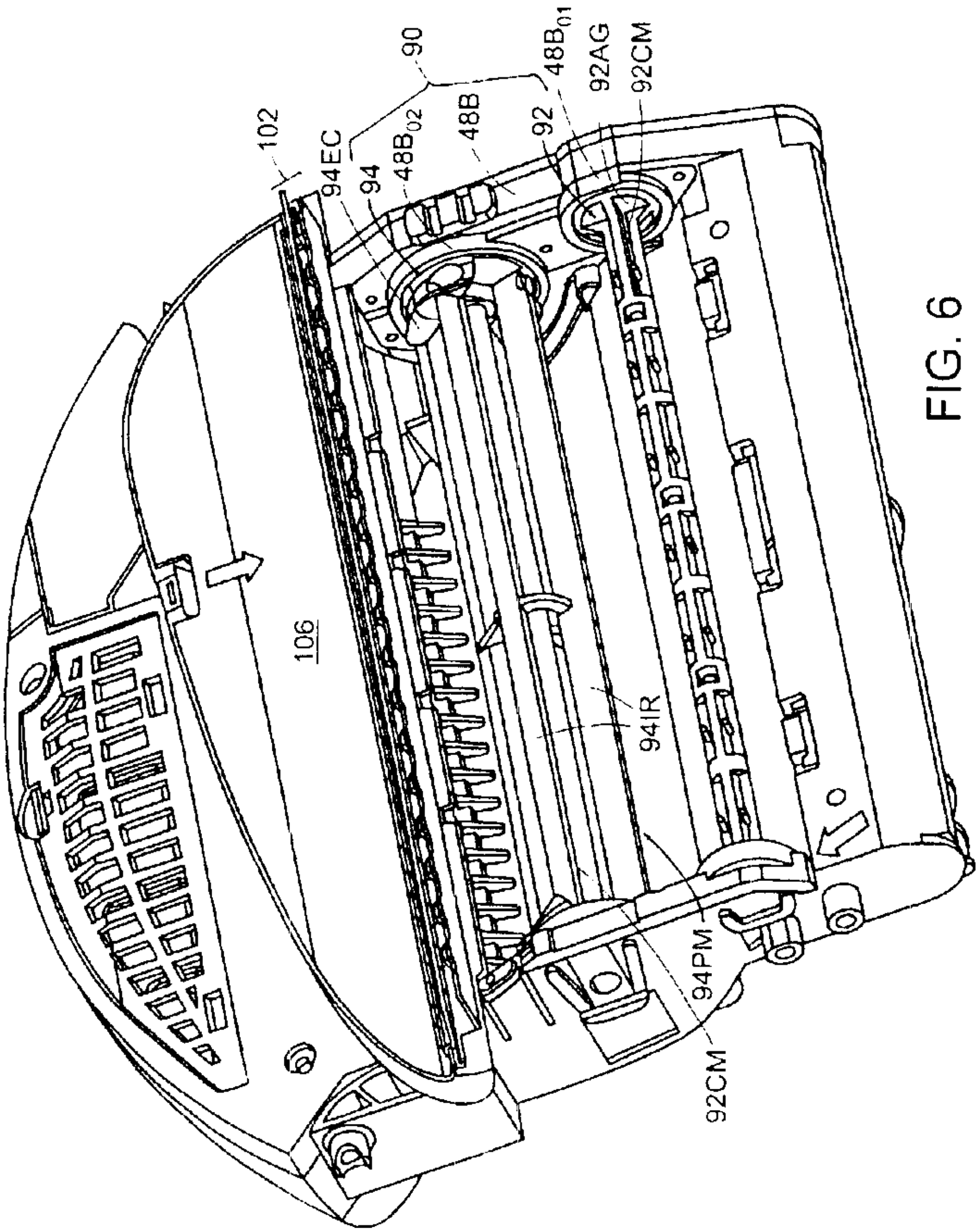
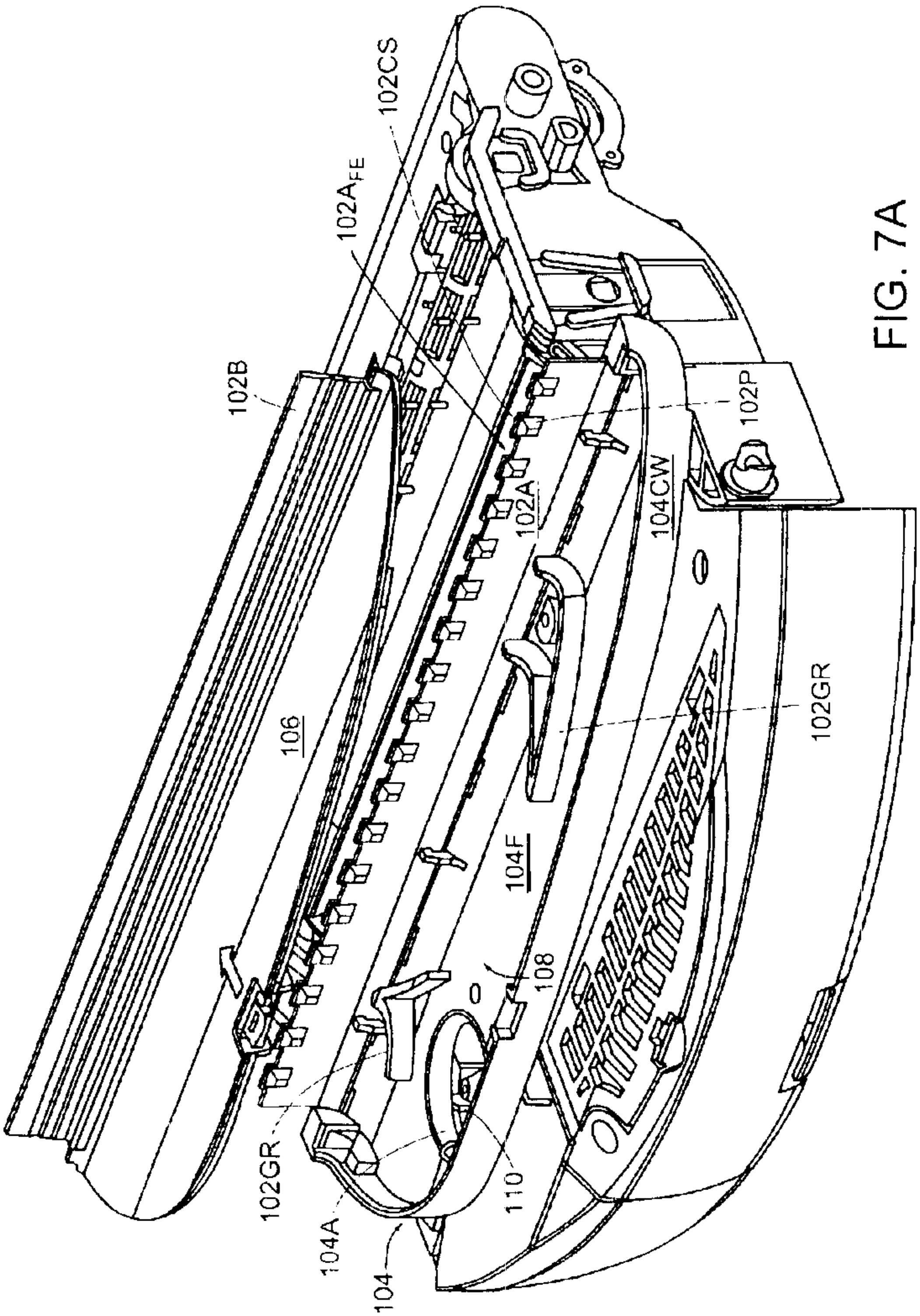


FIG. 6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104F
108
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110
104A
104

FIG. 7A

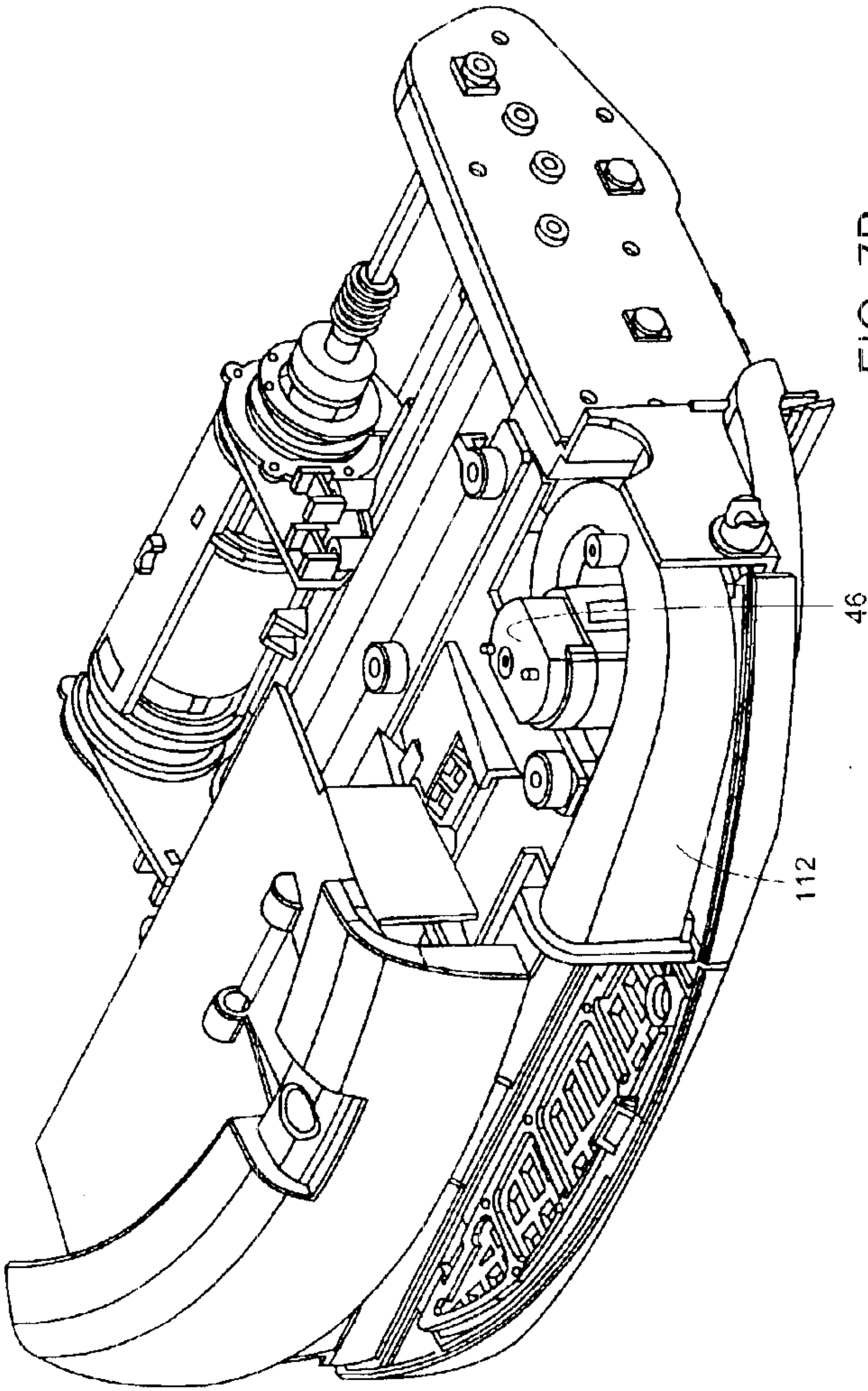

FIG. 7B

AUTONOMOUS FLOOR-CLEANING ROBOT

CROSS-REFERENCE TO RELATED APPLICATIONS

The subject matter of this application claims priority from U.S. Provisional Application Ser. No. 60/345,764 filed Jan. 3, 2002, entitled CLEANING MECHANISMS FOR AUTONOMOUS ROBOT. The subject matter of this application is also related to commonly-owned, co-pending U.S. patent application Ser. Nos. 09/768,773, filed Jan. 24, 2001, entitled ROBOT OBSTACLE DETECTION SYSTEM; 10/167,851, filed Jun. 12, 2002, entitled METHOD AND SYSTEM FOR ROBOT LOCALIZATION AND CONFINEMENT; and, 10/056,804, filed Jan. 24, 2002, entitled METHOD AND SYSTEM FOR MULTI-MODE COVERAGE FOR AN AUTONOMOUS ROBOT.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates to cleaning devices, and more particularly, to an autonomous floor-cleaning robot that comprises a self-adjustable cleaning head subsystem that includes a dual-stage brush assembly having counter-rotating, asymmetric brushes and an adjacent, but independent, vacuum assembly such that the cleaning capability and efficiency of the self-adjustable cleaning head subsystem is optimized while concomitantly minimizing the power requirements thereof. The autonomous floor-cleaning robot further includes a side brush assembly for directing particulates outside the envelope of the robot into the self-adjustable cleaning head subsystem.

(2) Description of Related Art

Autonomous robot cleaning devices are known in the art. For example, U.S. Pat. Nos. 5,940,927 and 5,781,960 disclose an Autonomous Surface Cleaning Apparatus and a Nozzle Arrangement for a Self-Guiding Vacuum Cleaner. One of the primary requirements for an autonomous cleaning device is a self-contained power supply—the utility of an autonomous cleaning device would be severely degraded, if not outright eliminated, if such an autonomous cleaning device utilized a power cord to tap into an external power source.

And, while there have been distinct improvements in the energizing capabilities of self-contained power supplies such as batteries, today's self-contained power supplies are still time-limited in providing power. Cleaning mechanisms for cleaning devices such as brush assemblies and vacuum assemblies typically require large power loads to provide effective cleaning capability. This is particularly true where brush assemblies and vacuum assemblies are configured as combinations, since the brush assembly and/or the vacuum assembly of such combinations typically have not been designed or configured for synergic operation.

A need exists to provide an autonomous cleaning device that has been designed and configured to optimize the cleaning capability and efficiency of its cleaning mechanisms for synergic operation while concomitantly minimizing or reducing the power requirements of such cleaning mechanisms.

BRIEF SUMMARY OF THE INVENTION

One object of the present invention is to provide a cleaning device that is operable without human intervention to clean designated areas.

Another object of the present invention is to provide such an autonomous cleaning device that is designed and configured to optimize the cleaning capability and efficiency of its cleaning mechanisms for synergic operations while concomitantly minimizing the power requirements of such mechanisms.

These and other objects of the present invention are provided by one embodiment autonomous floor-cleaning robot according to the present invention that comprises a housing infrastructure including a chassis, a power subsystem; for providing the energy to power the autonomous floor-cleaning robot, a motive subsystem operative to propel the autonomous floor-cleaning robot for cleaning operations, a control module operative to control the autonomous floor-cleaning robot to effect cleaning operations, and a self-adjusting cleaning head subsystem that includes a deck mounted in pivotal combination with the chassis, a brush assembly mounted in combination with the deck and powered by the motive subsystem to sweep up particulates during cleaning operations, a vacuum assembly disposed in combination with the deck and powered by the motive subsystem to ingest particulates during cleaning operations, and a deck height adjusting subassembly mounted in combination with the motive subsystem for the brush assembly, the deck, and the chassis that is automatically operative in response to a change in torque in said brush assembly to pivot the deck with respect to said chassis and thereby adjust the height of the brushes from the floor. The autonomous floor-cleaning robot also includes a side brush assembly mounted in combination with the chassis and powered by the motive subsystem to entrain particulates outside the periphery of the housing infrastructure and to direct such particulates towards the self-adjusting cleaning head subsystem.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention and the attendant features and advantages thereof may be had by reference to the following detailed description of the invention when considered in conjunction with the accompanying drawings wherein:

FIG. **1** is a schematic representation of an autonomous floor-cleaning robot according to the present invention.

FIG. **2** is a perspective view of one embodiment of an autonomous floor-cleaning robot according to the present invention.

FIG. **2A** is a bottom plan view of the autonomous floor-cleaning robot of FIG. **2**.

FIG. **3A** is a top, partially-sectioned plan view, with cover removed, of another embodiment of an autonomous floor-cleaning robot according to the present invention.

FIG. **3B** is a bottom, partially-section plan view of the autonomous floor-cleaning robot embodiment of FIG. **3A**.

FIG. **3C** is a side, partially sectioned plan view of the autonomous floor-cleaning robot embodiment of FIG. **3A**.

FIG. **4A** is a top plan view of the deck and chassis of the autonomous floor-cleaning robot embodiment of FIG. **3A**.

FIG. **4B** is a cross-sectional view of FIG. **4A** taken along line B—B thereof.

FIG. **4C** is a perspective view of the deck-adjusting subassembly of autonomous floor-cleaning robot embodiment of FIG. **3A**.

FIG. **5A** is a first exploded perspective view of a dust cartridge for the autonomous floor-cleaning robot embodiment of FIG. **3A**.

FIG. **5B** is a second exploded perspective view of the dust cartridge of FIG. **5A**.

FIG. 6 is a perspective view of a dual-stage brush assembly including a flapper brush and a main brush for the autonomous floor-cleaning robot embodiment of FIG. 3A.

FIG. 7A is a perspective view illustrating the blades and vacuum compartment for the autonomous floor cleaning robot embodiment of FIG. 3A.

FIG. 7B is a partial perspective exploded view of the autonomous floor-cleaning robot embodiment of FIG. 7A.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings where like reference numerals identify corresponding or similar elements throughout the several views, FIG. 1 is a schematic representation of an autonomous floor-cleaning robot **10** according to the present invention. The robot **10** comprises a housing infrastructure **20**, a power subsystem **30**, a motive subsystem **40**, a sensor subsystem **50**, a control module **60**, a side brush assembly **70**, and a self-adjusting cleaning head subsystem **80**. The power subsystem **30**, the motive subsystem **40**, the sensor subsystem **50**, the control module **60**, the side brush assembly **70**, and the self-adjusting cleaning head subsystem **80** are integrated in combination with the housing infrastructure **20** of the robot **10** as described in further detail in the following paragraphs.

In the following description of the autonomous floor-cleaning robot **10**, use of the terminology "forward/fore" refers to the primary direction of motion of the autonomous floor-cleaning robot **10**, and the terminology fore-aft axis (see reference characters "FA" in FIGS. 3A, 3B) defines the forward direction of motion (indicated by arrowhead of the fore-aft axis FA), which is coincident with the fore-aft diameter of the robot **10**.

Referring to FIGS. 2, 2A, and 3A–3C, the housing infrastructure **20** of the robot **10** comprises a chassis **21**, a cover **22**, a displaceable bumper **23**, a nose wheel subassembly **24**, and a carrying handle **25**. The chassis **21** is preferably molded from a material such as plastic as a unitary element that includes a plurality of preformed wells, recesses, and structural members for, inter alia, mounting or integrating elements of the power subsystem **30**, the motive subsystem **40**, the sensor subsystem **50**, the side brush assembly **70**, and the self-adjusting cleaning head subsystem **80** in combination with the chassis **21**. The cover **22** is preferably molded from a material such as plastic as a unitary element that is complementary in configuration with the chassis **21** and provides protection of and access to elements/components mounted to the chassis **21** and/or comprising the self-adjusting cleaning head subsystem **80**. The chassis **21** and the cover **22** are detachably integrated in combination by any suitable means, e.g., screws, and in combination, the chassis **21** and cover **22** form a structural envelope of minimal height having a generally cylindrical configuration that is generally symmetrical along the fore-aft axis FA.

The displaceable bumper **23**, which has a generally arcuate configuration, is mounted in movable combination at the forward portion of the chassis **21** to extend outwardly therefrom, i.e., the normal operating position. The mounting configuration of the displaceable bumper is such that the bumper **23** is displaced towards the chassis **21** (from the normal operating position) whenever the bumper **23** encounters a stationary object or obstacle of predetermined mass, i.e., the displaced position, and returns to the normal operating position when contact with the stationary object or obstacle is terminated (due to operation of the control module **60** which, in response to any such displacement of the bumper **23**, implements a "bounce" mode that causes the robot **10** to evade the stationary object or obstacle and continue its cleaning routine, e.g., initiate a random—or weighted-random—turn to resume forward movement in a different direction). The mounting configuration of the displaceable bumper **23** comprises a pair of rotatable support members **23RSM**, which are operative to facilitate the movement of the bumper **23** with respect to the chassis **21**.

The pair of rotatable support members **23RSM** are symmetrically mounted about the fore-aft axis FA of the autonomous floor-cleaning robot **10** proximal the center of the displaceable bumper **23** in a V-configuration. One end of each support member **23RSM** is rotatably mounted to the chassis **21** by conventional means, e.g., pins/dowel and sleeve arrangement, and the other end of each support member **23RSM** is likewise rotatably mounted to the displaceable bumper **23** by similar conventional means. A biasing spring (not shown) is disposed in combination with each rotatable support member **23RSM** and is operative to provide the biasing force necessary to return the displaceable bumper **23** (through rotational movement of the support members **23RSM**) to the normal operating position whenever contact with a stationary object or obstacle is terminated.

The embodiment described herein includes a pair of bumper arms **23BA** that are symmetrically mounted in parallel about the fore-aft diameter FA of the autonomous floor-cleaning robot **10** distal the center of the displaceable bumper **23**. These bumper arms **23BA** do not per se provide structural support for the displaceable bumper **23**, but rather are a part of the sensor subsystem **50** that is operative to determine the location of a stationary object or obstacle encountered via the bumper **23**. One end of each bumper arm **23BA** is rigidly secured to the displaceable bumper **23** and the other end of each bumper arm **23BA** is mounted in combination with the chassis **21** in a manner, e.g., a slot arrangement such that, during an encounter with a stationary object or obstacle, one or both bumper arms **23BA** are linearly displaceable with respect to the chassis **21** to activate an associated sensor, e.g., IR break beam sensor, mechanical switch, capacitive sensor, which provides a corresponding signal to the control module **60** to implement the "bounce" mode. Further details regarding the operation of this aspect of the sensor subsystem **50**, as well as alternative embodiments of sensors having utility in detecting contact with or proximity to stationary objects or obstacles can be found in commonly-owned, co-pending U.S. patent application Ser. No. 10/056,804, filed Jan. 24, 2002, entitled METHOD AND SYSTEM FOR MULTI-MODE COVERAGE FOR AN AUTONOMOUS ROBOT.

The nose-wheel subassembly **24** comprises a wheel **24W** rotatably mounted in combination with a clevis member **24CM** that includes a mounting shaft. The clevis mounting shaft **24CM** is disposed in a well in the chassis **21** at the forward end thereof on the fore-aft diameter of the autonomous floor-cleaning robot **10**. A biasing spring **24BS** (hidden behind a leg of the clevis member **24CM** in FIG. 3C) is disposed in combination with the clevis mounting shaft **24CM** and operative to bias the nose-wheel subassembly **24** to an 'extended' position whenever the nose-wheel subassembly **24** loses contact with the surface to be cleaned. During cleaning operations, the weight of the autonomous floor-cleaning robot **10** is sufficient to overcome the force exerted by the biasing spring **24BS** to bias the nose-wheel subassembly **24** to a partially retracted or operating position wherein the wheel rotates freely over the surface to be

cleaned. Opposed triangular or conical wings 24TW extend outwardly from the ends of the clevis member to prevent the side of the wheel from catching on low obstacle during turning movements of the autonomous floor-cleaning robot **10**. The wings **24**TW act as ramps in sliding over bumps as the robot turns.

Ends **25**E of the carrying handle **25** are secured in pivotal combination with the cover **22** at the forward end thereof, centered about the fore-aft axis FA of the autonomous floor-cleaning robot **10**. With the autonomous floor-cleaning robot **10** resting on or moving over a surface to be cleaned, the carrying handle **25** lies approximately flush with the surface of the cover **22** (the weight of the carrying handle **25**, in conjunction with arrangement of the handle-cover pivot configuration, is sufficient to automatically return the carrying handle **25** to this flush position due to gravitational effects). When the autonomous floor-cleaning robot **10** is picked up by means of the carrying handle **25**, the aft end of the autonomous floor-cleaning robot **10** lies below the forward end of the autonomous floor-cleaning robot **10** so that particulate debris is not dislodged from the self-adjusting cleaning head subsystem **80**.

The power subsystem **30** of the described embodiment provides the energy to power individual elements/components of the motive subsystem **40**, the sensor subsystem **50**, the side brush assembly **70**, and the self-adjusting cleaning head subsystem **80** and the circuits and components of the control module **60** via associated circuitry **32-4**, **32-5**, **32-7**, **32-8**, and **32-6**, respectively (see FIG. 1) during cleaning operations. The power subsystem **30** for the described embodiment of the autonomous floor-cleaning robot **10** comprises a rechargeable battery pack **34** such as a NiMH battery pack. The rechargeable battery pack **34** is mounted in a well formed in the chassis **21** (sized specifically for mounting/retention of the battery pack **34**) and retained therein by any conventional means, e.g., spring latches (not shown). The battery well is covered by a lid **34**L secured to the chassis **21** by conventional means such as screws. Affixed to the lid **34**L are friction pads **36** that facilitate stopping of the autonomous floor-cleaning robot **10** during automatic shutdown. The friction pads **36** aid in stopping the robot upon the robot's attempting to drive over a cliff. The rechargeable battery pack **34** is configured to provide sufficient power to run the autonomous floor-cleaning robot **10** for a period of sixty (60) to ninety (90) minutes on a full charge while meeting the power requirements of the elements/components comprising motive subsystem **40**, the sensor subsystem **50**, the side brush assembly **70**, the self-adjusting cleaning head subsystem **80**, and the circuits and components of the control module **60**.

The motive subsystem **40** comprises the independent means that: (1) propel the autonomous floor-cleaning robot **10** for cleaning operations; (2) operate the side brush assembly **70**; and (3) operate the self-adjusting cleaning head subsystem **80** during such cleaning operations. Such independent means includes right and left main wheel subassemblies **42**A, **42**B, each subassembly **42**A, **42**B having its own independently-operated motor **42**A_M, **42**B_M, respectively, an independent electric motor **44** for the side brush assembly **70**, and two independent electric motors **46**, **48** for the self-adjusting brush subsystem **80**, one motor **46** for the vacuum assembly and one motor **48** for the dual-stage brush assembly.

The right and left main wheel subassemblies **42**A, **42**B are independently mounted in wells of the chassis **21** formed at opposed ends of the transverse diameter of the chassis **21** (the transverse diameter is perpendicular to the fore-aft axis FA of the robot **10**). Mounting at this location provides the autonomous floor-cleaning robot **10** with an enhanced turning capability, since the main wheel subassemblies **42**A, **42**B motor can be independently operated to effect a wide range of turning maneuvers, e.g., sharp turns, gradual turns, turns in place.

Each main wheel subassembly **42**A, **42**B comprises a wheel **42**A_W, **42**B_W, rotatably mounted in combination with a clevis member **42**A_{CM}, **42**B_{CM}. Each clevis member **42**A_{CM}, **42**B_{CM} is pivotally mounted to the chassis **21** aft of the wheel axis of rotation (see FIG. 3C which illustrates the wheel axis of rotation **42**A_{AR}; the wheel axis of rotation for wheel subassembly **42**B, which is not shown, is identical), i.e., independently suspended. The aft pivot axis **42**A_{PA}, **42**B_{PA} (see FIG. 3A) of the main wheel subassemblies **42**A, **42**B facilitates the mobility of the autonomous floor-cleaning robot **10**, i.e., pivotal movement of the subassemblies **42**A, **42**B through a predetermined arc. The motor **42**A_M, **42**B_M associated with each main wheel subassembly **42**A, **42**B is mounted to the aft end of the clevis member **42**A_{CM}, **42**B_{CM}. One end of a tension spring **42**B_{TS} (the tension spring for the right wheel subassembly **42**A is not illustrated, but is identical to the tension spring **42**BTS of the left wheel subassembly **42**A) is attached to the aft portion of the clevis member **42**B_{CM} and the other end of the tension spring **42**B_{TS} is attached to the chassis **21** forward of the respective wheel **42**A_W, **42**B_W.

Each tension spring is operative to rotatably bias the respective main wheel subassembly **42**A, **42**B (via pivotal movement of the corresponding clevis member **42**A_{CM}, **42**B_{CM} through the predetermined arc) to an 'extended' position when the autonomous floor-cleaning robot **10** is removed from the floor (in this 'extended' position the wheel axis of rotation lies below the bottom plane of the chassis **21**). With the autonomous floor-cleaning robot **10** resting on or moving over a surface to be cleaned, the weight of autonomous floor-cleaning robot **10** gravitationally biases each main wheel subassembly **42**A, **42**B into a retracted or operating position wherein axis of rotation of the wheels are approximately coplanar with bottom plane of the chassis **21**. The motors **42**A_M, **42**B_M of the main wheel subassemblies **42**A, **42**B are operative to drive the main wheels: (1) at the same speed in the same direction of rotation to propel the autonomous floor-cleaning robot **10** in a straight line, either forward or aft; (2) at different speeds (including the situation wherein one wheel is operated at zero speed) to effect turning patterns for the autonomous floor-cleaning robot **10**; or (3) at the same speed in opposite directions of rotation to cause the robot **10** to turn in place, i.e., "spin on a dime". The wheels **42**A_W, **42**B_W of the main wheel subassemblies **42**A, **42**B preferably have a "knobby" tread configuration **42**A_{KT}, **42**B_{KT}. This knobby tread configuration **42**A_{KT}, **42**B_{KT} provides the autonomous floor-cleaning robot **10** with enhanced traction, particularly when traversing smooth surfaces and traversing between contiguous surfaces of different textures, e.g., bare floor to carpet or vice versa. This knobby tread configuration **42**A_{KT}, **42**B_{KT} also prevents tufted fabric of carpets/rugs from being entrapped in the wheels **42**A_W, **42**B and entrained between the wheels and the chassis **21** during movement of the autonomous floor-cleaning robot **10**. One skilled in the art will appreciate, however, that other tread patterns/configurations are within the scope of the present invention.

The sensor subsystem **50** comprises a variety of different sensing units that may be broadly characterized as either: (1) control sensing units **52**; or (2) emergency sensing units **54**. As the names imply, control sensing units **52** are operative

to regulate the normal operation of the autonomous floor-cleaning robot **10** and emergency sensing units **54** are operative to detect situations that could adversely affect the operation of the autonomous floor-cleaning robot **10** (e.g., stairs descending from the surface being cleaned) and provide signals in response to such detections so that the autonomous floor-cleaning robot **10** can implement an appropriate response via the control module **60**. The control sensing units **52** and emergency sensing units **54** of the autonomous floor-cleaning robot **10** are summarily described in the following paragraphs; a more complete description can be found in commonly-owned, co-pending U.S. patent application Ser. Nos. 09/768,773, filed Jan. 24, 2001, entitled ROBOT OBSTACLE DETECTION SYSTEM, 10/167,851, Jun. 12, 2002, entitled METHOD AND SYSTEM FOR ROBOT LOCALIZATION AND CONFINEMENT, and 10/056,804, filed Jan. 24, 2002, entitled METHOD AND SYSTEM FOR MULTI-MODE COVERAGE FOR AN AUTONOMOUS ROBOT.

The control sensing units **52** include obstacle detection sensors **52OD** mounted in conjunction with the linearly-displaceable bumper arms **23BA** of the displaceable bumper **23**, a wall-sensing assembly **52WS** mounted in the right-hand portion of the displaceable bumper **23**, a virtual wall sensing assembly **52VWS** mounted atop the displaceable bumper **23** along the fore-aft diameter of the autonomous floor-cleaning robot **10**, and an IR sensor/encoder combination **52WE** mounted in combination with each wheel subassembly **42A, 42B**.

Each obstacle detection sensor **52OD** includes an emitter and detector combination positioned in conjunction with one of the linearly displaceable bumper arms **23BA** so that the sensor **52OD** is operative in response to a displacement of the bumper arm **23BA** to transmit a detection signal to the control module **60**. The wall sensing assembly **52WS** includes an emitter and detector combination that is operative to detect the proximity of a wall or other similar structure and transmit a detection signal to the control module **60**. Each IR sensor/encoder combination **52WE** is operative to measure the rotation of the associated wheel subassembly **42A, 42B** and transmit a signal corresponding thereto to the control module **60**.

The virtual wall sensing assembly **52VWS** includes detectors that are operative to detect a force field and a collimated beam emitted by a stand-alone emitter (the virtual wall unit—not illustrated) and transmit respective signals to the control module **60**. The autonomous floor cleaning robot **10** is programmed not to pass through the collimated beam so that the virtual wall unit can be used to prevent the robot **10** from entering prohibited areas, e.g., access to a descending staircase, room not to be cleaned. The robot **10** is further programmed to avoid the force field emitted by the virtual wall unit, thereby preventing the robot **10** from overrunning the virtual wall unit during floor cleaning operations.

The emergency sensing units **54** include 'cliff detector' assemblies **54CD** mounted in the displaceable bumper **23**, wheeldrop assemblies **54WD** mounted in conjunction with the left and right main wheel subassemblies **42A, 42B** and the nose-wheel assembly **24**, and current stall sensing units **54CS** for the motor $\mathbf{42A}_M$, $\mathbf{42B}_M$ of each main wheel subassembly **42A, 42B** and one for the motors **44, 48** (these two motors are powered via a common circuit in the described embodiment). For the described embodiment of the autonomous floor-cleaning robot **10**, four (4) cliff detector assemblies **54CD** are mounted in the displaceable bumper **23**. Each cliff detector assembly **54CD** includes an emitter and detector combination that is operative to detect a predetermined drop in the path of the robot **10**, e.g., descending stairs, and transmit a signal to the control module **60**. The wheeldrop assemblies **54WD** are operative to detect when the corresponding left and right main wheel subassemblies **32A, 32B** and/or the nose-wheel assembly **24** enter the extended position, e.g., a contact switch, and to transmit a corresponding signal to the control module **60**. The current stall sensing units **54CS** are operative to detect a change in the current in the respective motor, which indicates a stalled condition of the motor's corresponding components, and transmit a corresponding signal to the control module **60**.

The control module **60** comprises the control circuitry (see, e.g., control lines **60-4, 60-5, 60-7**, and **60-8** in FIG. **1**) and microcontroller for the autonomous floor-cleaning robot **10** that controls the movement of the robot **10** during floor cleaning operations and in response to signals generated by the sensor subsystem **50**. The control module **60** of the autonomous floor-cleaning robot **10** according to the present invention is preprogrammed (hardwired, software, firmware, or combinations thereof) to implement three basic operational modes, i.e., movement patterns, that can be categorized as: (1) a "spot-coverage" mode; (2) a "wall/obstacle following" mode; and (3) a "bounce" mode. In addition, the control module **60** is preprogrammed to initiate actions based upon signals received from sensor subsystem **50**, where such actions include, but are not limited to, implementing movement patterns (2) and (3), an emergency stop of the robot **10**, or issuing an audible alert. Further details regarding the operation of the robot **10** via the control module **60** are described in detail in commonly-owned, co-pending U.S. patent application Ser. Nos. 09/768,773, filed Jan. 24, 2001, entitled ROBOT OBSTACLE DETECTION SYSTEM, 10/167,851, filed Jun. 12, 2002, entitled METHOD AND SYSTEM FOR ROBOT LOCALIZATION AND CONFINEMENT, and 10/056,804, filed Jan. 24, 2002, entitled METHOD AND SYSTEM FOR MULTI-MODE COVERAGE FOR AN AUTONOMOUS ROBOT.

The side brush assembly **70** is operative to entrain macroscopic and microscopic particulates outside the periphery of the housing infrastructure **20** of the autonomous floor-cleaning robot **10** and to direct such particulates towards the self-adjusting cleaning head subsystem **80**. This provides the robot **10** with the capability of cleaning surfaces adjacent to baseboards (during the wall-following mode).

The side brush assembly **70** is mounted in a recess formed in the lower surface of the right forward quadrant of the chassis **21** (forward of the right main wheel subassembly **42A** just behind the right hand end of the displaceable bumper **23**). The side brush assembly **70** comprises a shaft **72** having one end rotatably connected to the electric motor **44** for torque transfer, a hub **74** connected to the other end of the shaft **72**, a cover plate **75** surrounding the hub **74**, a brush means **76** affixed to the hub **74**, and a set of bristles **78**.

The cover plate **75** is configured and secured to the chassis **21** to encompass the hub **74** in a manner that prevents the brush means **76** from becoming stuck under the chassis **21** during floor cleaning operations.

For the embodiment of FIGS. 3A–3C, the brush means **76** comprises opposed brush arms that extend outwardly from the hub **74**. These brush arms **76** are formed from a compliant plastic or rubber material in an "L"/hockey stick configuration of constant width. The configuration and composition of the brush arms **76**, in combination, allows the brush arms **76** to resiliently deform if an obstacle or obstruction is temporarily encountered during cleaning operations.

Concomitantly, the use of opposed brush arms **76** of constant width is a trade-off (versus using a full or partial circular brush configuration) that ensures that the operation of the brush means **76** of the side brush assembly **70** does not adversely impact (i.e., by occlusion) the operation of the adjacent cliff detector subassembly **54**CD (the left-most cliff detector subassembly **54**CD in FIG. 3B) in the displaceable bumper **23**. The brush arms **76** have sufficient length to extend beyond the outer periphery of the autonomous floor-cleaning robot **10**, in particular the displaceable bumper **23** thereof. Such a length allows the autonomous floor-cleaning robot **10** to clean surfaces adjacent to baseboards (during the wall-following mode) without scrapping of the wall/baseboard by the chassis **21** and/or displaceable bumper **23** of the robot **10**.

The set of bristles **78** is set in the outermost free end of each brush arm **76** (similar to a toothbrush configuration) to provide the sweeping capability of the side brush assembly **70**. The bristles **78** have a length sufficient to engage the surface being cleaned with the main wheel subassemblies **42**A, **42**B and the nose-wheel subassembly **24** in the operating position.

The self-adjusting cleaning head subsystem **80** provides the cleaning mechanisms for the autonomous floor-cleaning robot **10** according to the present invention. The cleaning mechanisms for the preferred embodiment of the self-adjusting cleaning head subsystem **80** include a brush assembly **90** and a vacuum assembly **100**.

For the described embodiment of FIGS. 3A–3C, the brush assembly **90** is a dual-stage brush mechanism, and this dual-stage brush assembly **90** and the vacuum assembly **100** are independent cleaning mechanisms, both structurally and functionally, that have been adapted and designed for use in the robot **10** to minimize the over-all power requirements of the robot **10** while simultaneously providing an effective cleaning capability. In addition to the cleaning mechanisms described in the preceding paragraph, the self-adjusting cleaning subsystem **80** includes a deck structure **82** pivotally coupled to the chassis **21**, an automatic deck adjusting subassembly **84**, a removable dust cartridge **86**, and one or more bails **88** shielding the dual-stage brush assembly **90**.

The deck **82** is preferably fabricated as a unitary structure from a material such as plastic and includes opposed, spaced-apart sidewalls **82**SW formed at the aft end of the deck **82** (one of the sidewalls **82**SW comprising a U-shaped structure that houses the motor **46**, a brush-assembly well **82**W, a lateral aperture **82**LA formed in the intermediate portion of the lower deck surface, which defines the opening between the dual-stage brush assembly **90** and the removable dust cartridge **86**, and mounting brackets **82**MB formed in the forward portion of the upper deck surface for the motor **48**.

The sidewalls **82**SW are positioned and configured for mounting the deck **82** in pivotal combination with the chassis **21** by a conventional means, e.g., a revolute joint (see reference characters **82**RJ in FIG. 3A). The pivotal axis of the deck **82** chassis **21** combination is perpendicular to the fore—aft axis FA of the autonomous floor-cleaning robot **10** at the aft end of the robot **10** (see reference character **82**PA which identifies the pivotal axis in FIG. 3A).

The mounting brackets **82**MB are positioned and configured for mounting the constant-torque motor **48** at the forward lip of the deck **82**. The rotational axis of the mounted motor **48** is perpendicular to the fore—aft diameter of the autonomous floor-cleaning robot **10** (see reference character **48**RA which identifies the rotational axis of the motor **48** in FIG. 3A). Extending from the mounted motor **48** is an shaft **48**S for transferring the constant torque to the input side of a stationary, conventional dual-output gearbox **48**B (the housing of the dual-output gearbox **48**B is fabricated as part of the deck **82**).

The desk adjusting subassembly **84**, which is illustrated in further detail in FIGS. 4A–4C, is mounted in combination with the motor **48**, the deck **82** and the chassis **21** and operative, in combination with the electric motor **48**, to provide the physical mechanism and motive force, respectively, to pivot the deck **82** with respect to the chassis **21** about pivotal axis 82_{PA} whenever the dual-stage brush assembly **90** encounters a situation that results in a predetermined reduction in the rotational speed of the dual-stage brush assembly **90**. This situation, which most commonly occurs as the autonomous floor-cleaning robot **10** transitions between a smooth surface such as a floor and a carpeted surface, is characterized as the 'adjustment mode' in the remainder of this description.

The deck adjusting subassembly **84** for the described embodiment of FIG. 3A includes a motor cage **84**MC, a pulley **84**P, a pulley cord **84**C, an anchor member **84**AM, and complementary cage stops **84**CS. The motor **48** is non-rotatably secured within the motor cage **84**MC and the motor cage **84**MC is mounted in rotatable combination between the mounting brackets **82**MB. The pulley **84**P is fixedly secured to the motor cage **84**MC on the opposite side of the interior mounting bracket **82**MB in such a manner that the shaft **48**S of the motor **48** passes freely through the center of the pulley **84**P. The anchor member **84**AM is fixedly secured to the top surface of the chassis **21** in alignment with the pulley **84**P.

One end of the pulley cord **84**C is secured to the anchor member **84**AM and the other end is secured to the pulley **84**P in such a manner, that with the deck **82** in the 'down' or non-pivoted position, the pulley cord **84**C is tensioned. One of the cage stops **84**CS is affixed to the motor cage **84**MC; the complementary cage stop **84**CS is affixed to the deck **82**. The complementary cage stops **84**CS are in abutting engagement when the deck **82** is in the 'down' position during normal cleaning operations due to the weight of the self-adjusting cleaning head subsystem **80**.

During normal cleaning operations, the torque generated by the motor **48** is transferred to the dual-stage brush subassembly **90** by means of the shaft **48**S through the dual-output gearbox **48**B. The motor cage assembly is prevented from rotating by the counter-acting torque generated by the pulley cord **84**C on the pulley **84**P. When the resistance encountered by the rotating brushes changes, the deck height will be adjusted to compensate for it. If for example, the brush torque increases as the machine rolls from a smooth floor onto a carpet, the torque output of the motor **48** will increase. In response to this, the output torque of the motor **48** will increase. This increased torque overcomes the counter-acting torque exerted by the pulley cord **84**C on the pulley **84**P. This causes the pulley **84**P to rotate, effectively pulling itself up the pulley cord **84**C. This in turn, pivots the deck about the pivot axis, raising the brushes, reducing the friction between the brushes and the floor, and reducing the torque required by the dual-stage brush subassembly **90**. This continues until the torque between the motor **48** and the counteracting torque generated by the pulley cord **84**C on the pulley **84**P are once again in equilibrium and a new deck height is established.

In other words, during the adjustment mode, the foregoing torque transfer mechanism is interrupted since the shaft **48**S

is essentially stationary. This condition causes the motor **48** to effectively rotate about the shaft **48S**. Since the motor **48** is non-rotatably secured to the motor cage **84MC**, the motor cage **84MC**, and concomitantly, the pulley **84P**, rotate with respect to the mounting brackets **82MB**. The rotational motion imparted to the pulley **84P** causes the pulley **84P** to 'climb up' the pulley cord **84PC** towards the anchor member **84AM**. Since the motor cage **84MC** is effectively mounted to the forward lip of the deck **82** by means of the mounting brackets **82MB**, this movement of the pulley **84P** causes the deck **82** to pivot about its pivot axis **82PA** to an "up" position (see FIG. **4C**). This pivoting motion causes the forward portion of the deck **82** to move away from surface over which the autonomous floor-cleaning robot is traversing.

Such pivotal movement, in turn, effectively moves the dual-stage brush assembly **90** away from the surface it was in contact with, thereby permitting the dual-stage brush assembly **90** to speed up and resume a steady-state rotational speed (consistent with the constant torque transferred from the motor **48**). At this juncture (when the dual-stage brush assembly **90** reaches its steady-state rotational speed), the weight of the forward edge of the deck **82** (primarily the motor **48**), gravitationally biases the deck **82** to pivot back to the 'down' or normal state, i.e., planar with the bottom surface of the chassis **21**, wherein the complementary cage stops **84CS** are in abutting engagement.

While the deck adjusting subassembly **84** described in the preceding paragraphs is the preferred pivoting mechanism for the autonomous floor-cleaning robot **10** according to the present invention, one skilled in the art will appreciate that other mechanisms can be employed to utilize the torque developed by the motor **48** to induce a pivotal movement of the deck **82** in the adjustment mode. For example, the deck adjusting subassembly could comprise a spring-loaded clutch mechanism such as that shown in FIG. **4C** (identified by reference characters SLCM) to pivot the deck **82** to an "up" position during the adjustment mode, or a centrifugal clutch mechanism or a torque-limiting clutch mechanism. In other embodiments, motor torque can be used to adjust the height of the cleaning head by replacing the pulley with a cam and a constant force spring or by replacing the pulley with a rack and pinion, using either a spring or the weight of the cleaning head to generate the counter-acting torque.

The removable dust cartridge **86** provides temporary storage for macroscopic and microscopic particulates swept up by operation of the dual-stage brush assembly **90** and microscopic particulates drawn in by the operation of the vacuum assembly **100**. The removable dust cartridge **86** is configured as a dual chambered structure, having a first storage chamber **86SC1** for the macroscopic and microscopic particulates swept up by the dual-stage brush assembly **90** and a second storage chamber **86SC2** for the microscopic particulates drawn in by the vacuum assembly **100**. The removable dust cartridge **86** is further configured to be inserted in combination with the deck **82** so that a segment of the removable dust cartridge **86** defines part of the rear external sidewall structure of the autonomous floor-cleaning robot **10**.

As illustrated in FIGS. **5A–5B**, the removable dust cartridge **86** comprises a floor member **86FM** and a ceiling member **86CM** joined together by opposed sidewall members **86SW**. The floor member **86FM** and the ceiling member **86CM** extend beyond the sidewall members **86SW** to define an open end **86E**, and the free end of the floor member **86FM** is slightly angled and includes a plurality of baffled projections **86AJ** to remove debris entrained in the brush mechanisms of the dual-stage brush assembly **90**, and to facilitate

insertion of the removable dust cartridge **86** in combination with the deck **82** as well as retention of particulates swept into the removable dust cartridge **86**. A backwall member **86**BW is mounted between the floor member **86**FM and the ceiling member **86**CM distal the open end **86**E in abutting engagement with the sidewall members **86**SW. The backwall member **86**BW has an baffled configuration for the purpose of deflecting particulates angularly therefrom to prevent particulates swept up by the dual-stage brush assembly **90** from ricocheting back into the brush assembly **90**. The floor member **86**FM, the ceiling member **86**CM, the sidewall members **86**SW, and the backwall member **86**BW in combination define the first storage chamber **86SC1**.

The removable dust cartridge **86** further comprises a curved arcuate member **86CAM** that defines the rear external sidewall structure of the autonomous floor-cleaning robot **10**. The curved arcuate member **86CAM** engages the ceiling member **86CM**, the floor member **86F** and the sidewall members **86SW**. There is a gap formed between the curved arcuate member **86CAM** and one sidewall member **86SW** that defines a vacuum inlet **86VI** for the removable dust cartridge **86**. A replaceable filter **86RF** is configured for snap fit insertion in combination with the floor member **86FM**. The replaceable filter **86RF**, the curved arcuate member **86CAM**, and the backwall member **86BW** in combination define the second storage chamber **86SC1**.

The removable dust cartridge **86** is configured to be inserted between the opposed spaced-apart sidewalls **82SW** of the deck **82** so that the open end of the removable dust cartridge **86** aligns with the lateral aperture **82LA** formed in the deck **82**. Mounted to the outer surface of the ceiling member **86CM** is a latch member **86LM**, which is operative to engage a complementary shoulder formed in the upper surface of the deck **82** to latch the removable dust cartridge **86** in integrated combination with the deck **82**.

The bail **88** comprises one or more narrow gauge wire structures that overlay the dual-stage brush assembly **90**. For the described embodiment, the bail **88** comprises a continuous narrow gauge wire structure formed in a castellated configuration, i.e., alternating open-sided rectangles. Alternatively, the bail **88** may comprise a plurality of single, open-sided rectangles formed from narrow gauge wire. The bail **88** is designed and configured for press fit insertion into complementary retaining grooves **88A**, **88B**, respectively, formed in the deck **82** immediately adjacent both sides of the dual-stage brush assembly **90**. The bail **88** is operative to shield the dual-stage brush assembly **90** from larger external objects such as carpet tassels, tufted fabric, rug edges, during cleaning operations, i.e., the bail **88** deflects such objects away from the dual-stage brush assembly **90**, thereby preventing such objects from becoming entangled in the brush mechanisms.

The dual-stage brush assembly **90** for the described embodiment of FIG. **2A** comprises a flapper brush **92** and a main brush **94** that are generally illustrated in FIG. **6**. Structurally, the flapper brush **92** and the main brush **94** are asymmetric with respect to one another, with the main brush **94** having an O.D. greater than the O.D. of the flapper brush **92**. The flapper brush **92** and the main brush **94** are mounted in the deck **82** recess, as described below in further detail, to have minimal spacing between the sweeping peripheries defined by their respective rotating elements. Functionally, the flapper brush **92** and the main brush **94** counter-rotate with respect to one another, with the flapper brush **92** rotating in a first direction that causes macroscopic particulates to be directed into the removable dust cartridge **86** and the main brush **94** rotating in a second direction, which is

opposite to the forward movement of the autonomous floor-cleaning robot **10**, that causes macroscopic and microscopic particulates to be directed into the removable dust cartridge **86**. In addition, this rotational motion of the main brush **94** has the secondary effect of directing macroscopic and microscopic particulates towards the pick-up zone of the vacuum assembly **100** such that particulates that are not swept up by the dual-stage brush assembly **90** can be subsequently drawn up (ingested) by the vacuum assembly **100** due to movement of the autonomous floor-cleaning robot **10**.

The flapper brush **92** comprises a central member **92CM** having first and second ends. The first and second ends are designed and configured to mount the flapper brush **92** in rotatable combination with the deck **82** and a first output port $48B_{O1}$ of the dual output gearbox **48B**, respectively, such that rotation of the flapper brush **92** is provided by the torque transferred from the electric motor **48** (the gearbox **48B** is configured so that the rotational speed of the flapper brush **92** is relative to the speed of the autonomous floor-cleaning robot **10**—the described embodiment of the robot **10** has a top speed of approximately 0.9 ft/sec). In other embodiments, the flapper brush **92** rotates substantially faster than traverse speed either in relation or not in relation to the transverse speed. Axle guards **92AG** having a beveled configuration are integrally formed adjacent the first and second ends of the central member **92CM** for the purpose of forcing hair and other similar matter away from the flapper brush **92** to prevent such matter from becoming entangled with the ends of the central member **92CM** and stalling the dual-stage brush assembly **90**.

The brushing element of the flapper brush **92** comprises a plurality of segmented cleaning strips **92CS** formed from a compliant plastic material secured to and extending along the central member **92CM** between the internal ends of the axle guards **92AG** (for the illustrated embodiment, a sleeve, configured to fit over and be secured to the central member **92CM**, has integral segmented strips extending outwardly therefrom). The cleaning strips **92CS** can be arranged in a linear pattern as shown in the drawings (i.e. FIG. **2A** and FIG. **3B**) or alternatively in a herringbone or chevron pattern.

For the described embodiment, six (6) segmented cleaning strips **92CS** were equidistantly spaced circumferentially about die central member **92CM**. One skilled in the art will appreciate that more or less segmented cleaning strips **92CS** can be employed in the flapper brush **90** without departing from the scope of the present invention. Each of the cleaning strips **92S** is segmented at prescribed intervals, such segmentation intervals depending upon the configuration (spacing) between the wire(s) forming the bail **88**. The embodiment of the bail **88** described above resulted in each cleaning strip **92CS** of the described embodiment of the flapper brush **92** having five (5) segments.

The main brush **94** comprises a central member **94CM** (for the described embodiment the central member **94CM** is a round metal member having a spiral configuration)having first and second straight ends (i.e., aligned along the centerline of the spiral). Integrated in combination with the central member **94CM** is a segmented protective member **94PM**. Each segment of the protective member **94PM** includes opposed, spaced-apart, semi-circular end caps **94EC** having integral ribs **94IR** extending therebetween. For the described embodiment, each pair of semi-circular end caps EC has two integral ribs extending therebetween. The protective member **94PM** is assembled by joining complementary semi-circular end caps **94EC** by any conventional means, e.g., screws, such that assembled complementary end caps **94EC** have a circular configuration.

The protective member **94PM** is integrated in combination with the central member **94CM** so that the central member **94CM** is disposed along the centerline of the protective member **94PM**, and with the first end of the central member **94CM** terminating in one circular end cap **94EC** and the second end of the central member **94CM** extending through the other circular end cap **94EC**. The second end of the central member **94CM** is mounted in rotatable combination with the deck **82** and the circular end cap **94EC** associated with the first end of the central member **94CM** is designed and configured for mounting in rotatable combination with the second output port $48B_{O2}$ of the gearbox **48B** such that the rotation of the main brush **94** is provided by torque transferred from the electric motor **48** via the gearbox **48B**.

Bristles **94B** are set in combination with the central member **94CM** to extend between the integral ribs **94IR** of the protective member **94PM** and beyond the O.D. established by the circular end caps **94EC**. The integral ribs **94IR** are configured and operative to impede the ingestion of matter such as rug tassels and tufted fabric by the main brush **94**.

The bristles **94B** of the main brush **94** can be fabricated from any of the materials conventionally used to form bristles for surface cleaning operations. The bristles **94B** of the main brush **94** provide an enhanced sweeping capability by being specially configured to provide a "flicking" action with respect to particulates encountered during cleaning operations conducted by the autonomous floor-cleaning robot **10** according to the present invention. For the described embodiment, each bristle **94B** has a diameter of approximately 0.010 inches, a length of approximately 0.90 inches, and a free end having a rounded configuration. It has been determined that this configuration provides the optimal flicking action. While bristles having diameters exceeding approximately 0.014 inches would have a longer wear life, such bristles are too stiff to provide a suitable flicking action in the context of the dual-stage brush assembly **90** of the present invention. Bristle diameters that are much less than 0.010 inches are subject to premature wear out of the free ends of such bristles, which would cause a degradation in the sweeping capability of the main brush. In a preferred embodiment, the main brush is set slightly lower than the flapper brush to ensure that the flapper does not contact hard surface floors.

The vacuum assembly **100** is independently powered by means of the electric motor **46**. Operation of the vacuum assembly **100** independently of the self-adjustable brush assembly **90** allows a higher vacuum force to be generated and maintained using a battery-power source than would be possible if the vacuum assembly were operated in dependence with the brush system. In other embodiments, the main brush motor can drive the vacuum. Independent operation is used herein in the context that the inlet for the vacuum assembly **100** is an independent structural unit having dimensions that are not dependent upon the "sweep area" defined by the dual-stage brush assembly **90**.

The vacuum assembly **100**, which is located immediately aft of the dual-stage brush assembly **90**, i.e., a trailing edge vacuum, is orientated so that the vacuum inlet is immediately adjacent the main brush **94** of the dual-stage brush assembly **90** and forward facing, thereby enhancing the ingesting or vacuuming effectiveness of the vacuum assembly **100**. With reference to FIGS. **7A**, **7B**, the vacuum assembly **100** comprises a vacuum inlet **102**, a vacuum compartment **104**, a compartment cover **106**, a vacuum chamber **108**, an impeller **110**, and vacuum channel **112**. The

vacuum inlet **102** comprises first and second blades **102A**, **102B** formed of a semi-rigid/compliant plastic or elastomeric material, which are configured and arranged to provide a vacuum inlet **102** of constant size (lateral width and gap-see discussion below), thereby ensuring that the vacuum assembly **100** provides a constant air inflow velocity, which for the described embodiment is approximately 4 m/sec.

The first blade **102A** has a generally rectangular configuration, with a width (lateral) dimension such that the opposed ends of the first blade **102A** extend beyond the lateral dimension of the dual-stage brush assembly **90**. One lateral edge of the first blade **102A** is attached to the lower surface of the deck **82** immediately adjacent to but spaced apart from, the main brush **94** (a lateral ridge formed in the deck **82** provides the separation therebetween, in addition to embodying retaining grooves for the bail **88** as described above) in an orientation that is substantially symmetrical to the fore-aft diameter of the autonomous floor-cleaning robot **10**. This lateral edge also extends into the vacuum compartment **104** where it is in sealed engagement with the forward edge of the compartment **104**. The first blade **102A** is angled forwardly with respect to the bottom surface of the deck **82** and has length such that the free end **102A**$_{FE}$ of the first blade **102A** just grazes the surface to be cleaned.

The free end **102A**$_{FE}$ has a castellated configuration that prevents the vacuum inlet **102** from pushing particulates during cleaning operations. Aligned with the castellated segments **102CS** of the free end **102A**$_{FE}$, which are spaced along the width of the first blade **102A**, are protrusions **102P** having a predetermined height. For the prescribed embodiment, the height of such protrusions **102P** is approximately 2 mm. The predetermined height of the protrusions **102P** defines the "gap" between the first and second blades **102A**, **102B**.

The second blade **102B** has a planar, unitary configuration that is complementary to the first blade **102A** in width and length. The second blade **102B**, however, does not have a castellated free end; instead, the free end of the second blade **102B** is a straight edge. The second blade **102B** is joined in sealed combination with the forward edge of the compartment cover **106** and angled with respect thereto so as to be substantially parallel to the first blade **102A**. When the compartment cover **106** is fitted in position to the vacuum compartment **104**, the planar surface of the second blade **102B** abuts against the plurality of protrusions **102P** of the first blade **102A** to form the "gap" between the first and second blades **102A**, **102B**.

The vacuum compartment **104**, which is in fluid communication with the vacuum inlet **102**, comprises a recess formed in the lower surface of the deck **82**. This recess includes a compartment floor **104F** and a contiguous compartment wall **104CW** that delineates the perimeter of the vacuum compartment **104**. An aperture **104A** is formed through the floor **104**, offset to one side of the floor **104F**. Due to the location of this aperture **104A**, offset from the geometric center of the compartment floor **104F**, it is prudent to form several guide ribs **104GR** that project upwardly from the compartment floor **104F**. These guide ribs **104GR** are operative to distribute air inflowing through the gap between the first and second blades **102A**, **102B** across the compartment floor **104** so that a constant air inflow is created and maintained over the entire gap, i.e., the vacuum inlet **102** has a substantially constant 'negative' pressure (with respect to atmospheric pressure).

The compartment cover **106** has a configuration that is complementary to the shape of the perimeter of the vacuum compartment **104**. The cover **106** is further configured to be press fitted in sealed combination with the contiguous compartment wall **104CW** wherein the vacuum compartment **104** and the vacuum cover **106** in combination define the vacuum chamber **108** of the vacuum assembly **100**. The compartment cover **106** can be removed to clean any debris from the vacuum channel **112**. The compartment cover **106** is preferable fabricated from a clear or smoky plastic material to allow the user to visually determine when clogging occurs.

The impeller **110** is mounted in combination with the deck **82** in such a manner that the inlet of the impeller **110** is positioned within the aperture **104A**. The impeller **110** is operatively connected to the electric motor **46** so that torque is transferred from the motor **46** to the impeller **110** to cause rotation thereof at a constant speed to withdraw air from the vacuum chamber **108**. The outlet of the impeller **110** is integrated in sealed combination with one end of the vacuum channel **112**.

The vacuum channel **112** is a hollow structural member that is either formed as a separate structure and mounted to the deck **82** or formed as an integral part of the deck **82**. The other end of the vacuum channel **110** is integrated in sealed combination with the vacuum inlet **86VI** of the removable dust cartridge **86**. The outer surface of the vacuum channel **112** is complementary in configuration to the external shape of curved arcuate member **86CAM** of the removable dust cartridge **86**.

A variety of modifications and variations of the present invention are possible in light of the above teachings. For example, the preferred embodiment described above included a cleaning head subsystem **80** that was self-adjusting, i.e., the deck **82** was automatically pivotable with respect to the chassis **21** during the adjustment mode in response to a predetermined increase in brush torque of the dual-stage brush assembly **90**. It will be appreciated that another embodiment of the autonomous floor-cleaning robot according to the present invention is as described hereinabove, with the exception that the cleaning head subsystem is non-adjustable, i.e., the deck is non-pivotable with respect to the chassis. This embodiment would not include the deck adjusting subassembly described above, i.e., the deck would be rigidly secured to the chassis. Alternatively, the deck could be fabricated as an integral part of the chassis—in which case the deck would be a virtual configuration, i.e., a construct to simplify the identification of components comprising the cleaning head subsystem and their integration in combination with the robot.

It is therefore to be understood that, within the scope of the appended claims, the present invention may be practiced other than as specifically described herein.

What is claimed is:

1. A floor-cleaning robot, comprising:

a housing structure including a chassis,

a motive system operable to generate movement of the robot across a surface during floor-cleaning,

a vacuum system disposed at least in part within the chassis and operable to ingest particulates and thereby provide floor-cleaning,

a primary brush assembly operable to collect particulates from the surface during floor-cleaning,

a side brush assembly operable to cooperate with the vacuum system or the primary brush assembly to direct particulates outside the periphery of the housing structure, which would be otherwise outside the range of the vacuum system or the primary brush assembly, toward the vacuum system during floor-cleaning,

a removable dust cartridae operable to be removably integrated into the housing in communication with the vacuum system or the primary brush assembly, and operable to store particulates ingested by the vacuum system or collected by the primary brush assembly,

a sensor system operable to generate signals representative of conditions encountered by the robot during floor-cleaning, and

a control system, in communication with the motive system and responsive to signals generated by the sensor system to control movement of the robot,

wherein the sensor system comprises a cliff detector operable to generate a cliff signal upon detection of a cliff, and

the control system is responsive to the cliff signal to control movement of the robot upon detection of a cliff to enable the robot to escape from the cliff and to continue movement.

2. The robot of claim 1 wherein the control system is responsive to the cliff signal to reduce velocity of movement of the robot upon detection of a cliff.

3. The robot of claim 2 wherein the control system is responsive to the cliff signal to change direction of movement of the robot upon detection of a cliff.

4. The robot of claim 1 wherein:

the sensor system comprises an obstacle detection sensor operable to generate an obstacle signal upon detection of an obstacle, and

the control system is responsive to the obstacle signal to control movement of the robot upon detection of an obstacle.

5. The robot of claim 1 wherein:

the obstacle detection sensor comprises a tactile sensor, and

the control system is responsive to the obstacle signal generated by the tactile sensor to cause the robot to execute an escape behavior and continue movement.

6. The robot of claim 1 wherein:

the control system is configured to operate the robot in, and to select from any of a plurality of modes, the plurality of modes comprising:

a spot-coverage mode whereby the robot provides coverage of a spot on the floor,

an obstacle following mode whereby the robot travels adjacent to an obstacle, and

a bounce mode whereby the robot travels substantially in a direction away from an obstacle after encountering an obstacle.

* * * * *

JS 44 (Rev. 3/99)

CIVIL COVER SHEET

The JS-44 civil cover sheet and the information contained herein neither replace nor supplement the filing and service of pleadings or other papers as required by law, except as provided by local rules of court. This form, approved by the Judicial Conference of the United States in September 1974, is required for the use of the Clerk of Court for the purpose of initiating the civil docket sheet. (SEE INSTRUCTIONS ON THE REVERSE OF THE FORM.)

I. (a) PLAINTIFFS

iRobot Corporation

(b) County of Residence of First Listed Plaintiff Middlesex
(EXCEPT IN U.S. PLAINTIFF CASES)

DEFENDANTS

Urus Industrial Corporation
Koolatron, a division of Urus Industrial Corporation

County of Residence of First Listed Canada
(IN U.S. PLAINTIFF CASES ONLY)

NOTE: IN LAND CONDEMNATION CASES, USE THE LOCATION OF THE LAND INVOLVED.

(c) Attorney's (Firm Name, Address, and Telephone Number)

Ropes & Gray, LLP
One International Place
Boston, Massachusetts 02110

Attorneys (If Known)

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II. BASIS OF JURISDICTION (Place an "X" in One Box Only)

☐ 1 U.S. Government Plaintiff
☒ 3 Federal Question (U.S. Government Not a Party)
☐ 2 U.S. Government Defendant
☐ 4 Diversity (Indicate Citizenship of Parties in Item III)

III. CITIZENSHIP OF PRINCIPAL PARTIES (Place an "X" in One Box for Plaintiff and One Box for Defendant)
(For Diversity Cases Only)

	PTF	DEF		PTF	DEF
Citizen of This State	☐ 1	☐ 1	Incorporated or Principal Place of Business In This State	☐ 4	☐ 4
Citizen of Another State	☐ 2	☐ 2	Incorporated and Principal Place of Business In Another State	☐ 5	☐ 5
Citizen or Subject of a Foreign Country	☐ 3	☐ 3	Foreign Nation	☐ 6	☐ 6

IV. NATURE OF SUIT (Place an "X" in One Box Only)

CONTRACT
☐ 110 Insurance
☐ 120 Marine
☐ 130 Miller Act
☐ 140 Negotiable Instrument
☐ 150 Recovery of Overpayment & Enforcement of Judgment
☐ 151 Medicare Act
☐ 152 Recovery of Defaulted Student Loans (Excl. Veterans)
☐ 153 Recovery of Overpayment of Veteran's Benefits
☐ 160 Stockholders' Suits
☐ 190 Other Contract
☐ 195 Contract Product Liability

REAL PROPERTY
☐ 210 Land Condemnation
☐ 220 Foreclosure
☐ 230 Rent Lease & Ejectment
☐ 240 Torts to Land
☐ 245 Tort Product Liability
☐ 290 All Other Real Property

TORTS

PERSONAL INJURY
☐ 310 Airplane
☐ 315 Airplane Product Liability
☐ 320 Assault, Libel & Slander
☐ 330 Federal Employers' Liability
☐ 340 Marine
☐ 345 Marine Product Liability
☐ 350 Motor Vehicle
☐ 355 Motor Vehicle Product Liability
☐ 360 Other Personal Injury

PERSONAL INJURY
☐ 362 Personal Injury—Med. Malpractice
☐ 365 Personal Injury — Product Liability
☐ 368 Asbestos Personal Injury Product Liability

PERSONAL PROPERTY
☐ 370 Other Fraud
☐ 371 Truth in Lending
☐ 380 Other Personal Property Damage
☐ 385 Property Damage Product Liability

CIVIL RIGHTS
☐ 441 Voting
☐ 442 Employment
☐ 443 Housing/ Accommodations
☐ 444 Welfare
☐ 440 Other Civil Rights

PRISONER PETITIONS
☐ 510 Motions to Vacate Sentence
Habeas Corpus:
☐ 530 General
☐ 535 Death Penalty
☐ 540 Mandamus & Other
☐ 550 Civil Rights
☐ 555 Prison Condition

FORFEITURE/PENALTY
☐ 610 Agriculture
☐ 620 Other Food & Drug
☐ 625 Drug Related Seizure of Property 21 USC
☐ 630 Liquor Laws
☐ 640 R.R. & Truck
☐ 650 Airline Regs.
☐ 660 Occupational Safety/Health
☐ 690 Other

LABOR
☐ 710 Fair Labor Standards Act
☐ 720 Labor/Mgmt. Relations
☐ 730 Labor/Mgmt.Reporting & Disclosure Act
☐ 740 Railway Labor Act
☐ 790 Other Labor Litigation
☐ 791 Empl. Ret. Inc. Security Act

BANKRUPTCY
☐ 422 Appeal 28 USC 158
☐ 423 Withdrawal 28 USC 157

PROPERTY RIGHTS
☐ 820 Copyrights
☒ 830 Patent
☐ 840 Trademark

SOCIAL SECURITY
☐ 861 HIA (1395ff)
☐ 862 Black Lung (923)
☐ 863 DIWC/DIWW (405(g))
☐ 864 SSID Title XVI
☐ 865 RSI (405(g))

FEDERAL TAX SUITS
☐ 870 Taxes (U.S. Plaintiff or Defendant)
☐ 871 IRS—Third Party 26 USC 7609

OTHER STATUTES
☐ 400 State Reapportionment
☐ 410 Antitrust
☐ 430 Banks and Banking
☐ 450 Commerce/ICC Rates/etc.
☐ 460 Deportation
☐ 470 Racketeer Influenced and Corrupt Organizations
☐ 810 Selective Service
☐ 850 Securities/Commodities/ Exchange
☐ 875 Customer Challenge 12 USC 3410
☐ 891 Agricultural Acts
☐ 892 Economic Stabilization Act
☐ 893 Environmental Matters
☐ 894 Energy Allocation Act
☐ 895 Freedom of Information Act
☐ 900 Appeal of Fee Determination Under Equal Access to Justice
☐ 950 Constitutionality of State Statutes
☐ 890 Other Statutory Actions

V. ORIGIN (PLACE AN "X" IN ONE BOX ONLY)

☒ 1 Original Proceeding ☐ 2 Removed from State Court ☐ 3 Remanded from Appellate Court ☐ 4 Reinstated or Reopened ☐ 5 Transferred from another district (specify) ☐ 6 Multidistrict Litigation ☐ 7 Appeal to District Judge from Magistrate Judgment

VI. CAUSE OF ACTION (Cite the U.S. Civil Statute under which you are filing and write brief statement of cause. Do not cite jurisdictional statutes unless diversity.)

35 U.S.C. Section 1 - patent infringement, 17 U.S.C. Section 101 - copyright infringement
15 U.S.C. Section 1125(a) - Trade Dress Infringement

VII. REQUESTED IN COMPLAINT: ☐ CHECK IF THIS IS A CLASS ACTION UNDER F.R.C.P. 23 DEMAND $

CHECK YES only if demanded in complaint:
JURY DEMAND: ☐ Yes ☒ No

VIII. RELATED CASE(S) IF ANY (See instructions): JUDGE DOCKET NUMBER

5/3/2005
DATE SIGNATURE OF ATTORNEY OF RECORD

FOR OFFICE USE ONLY

RECEIPT # AMOUNT APPLYING IFP JUDGE MAG. JUDGE

UNITED STATES DISTRICT COURT
DISTRICT OF MASSACHUSETTS

1. TITLE OF CASE (NAME OF FIRST PARTY ON EACH SIDE ONLY) iRobot Corporation v. Urus Industrial Corporation

2. CATEGORY IN WHICH THE CASE BELONGS BASED UPON THE NUMBERED NATURE OF SUIT CODE LISTED ON THE CIVIL COVER SHEET. (SEE LOCAL RULE 40.1(A)(1)).

___	I.	160, 410, 470, R.23, REGARDLESS OF NATURE OF SUIT.	
x	II.	195, 368, 400, 440, 441-444, 540, 550, 555, 625, 710, 720, 730, 740, 790, 791, 820*, 830*, 840*, 850, 890, 892-894, 895, 950.	*Also complete AO 120 or AO 121 for patent, trademark or copyright cases
___	III.	110, 120, 130, 140, 151, 190, 210, 230, 240, 245, 290, 310, 315, 320, 330, 340, 345, 350, 355, 360, 362, 365, 370, 371, 380, 385, 450, 891.	
___	IV.	220, 422, 423, 430, 460, 510, 530, 610, 620, 630, 640, 650, 660, 690, 810, 861-865, 870, 871, 875, 900.	
___	V.	150, 152, 153.	

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3. TITLE AND NUMBER, IF ANY, OF RELATED CASES. (SEE LOCAL RULE 40.1(G)). IF MORE THAN ONE PRIOR RELATED CASE HAS BEEN FILED IN THIS DISTRICT PLEASE INDICATE THE TITLE AND NUMBER OF THE FIRST FILED CASE IN THIS COURT.

N/A

4. HAS A PRIOR ACTION BETWEEN THE SAME PARTIES AND BASED ON THE SAME CLAIM EVER BEEN FILED IN THIS COURT?

YES NO

5. DOES THE COMPLAINT IN THIS CASE QUESTION THE CONSTITUTIONALITY OF AN ACT OF CONGRESS AFFECTING THE PUBLIC INTEREST? (SEE 28 USC §2403)

YES NO

IF SO, IS THE U.S.A. OR AN OFFICER, AGENT OR EMPLOYEE OF THE U.S. A PARTY?

YES NO

6. IS THIS CASE REQUIRED TO BE HEARD AND DETERMINED BY A DISTRICT COURT OF THREE JUDGES PURSUANT TO TITLE 28 USC §2284?

YES NO

7. DO ALL OF THE PARTIES IN THIS ACTION, EXCLUDING GOVERNMENTAL AGENCIES OF THE UNITED STATES AND THE COMMONWEALTH OF MASSACHUSETTS ("GOVERNMENTAL AGENCIES"), RESIDING IN MASSACHUSETTS RESIDE IN THE SAME DIVISION? - (SEE LOCAL RULE 40.1(D)).

YES NO

A. IF YES, IN WHICH DIVISION DO ALL OF THE NON-GOVERNMENTAL PARTIES RESIDE?

EASTERN DIVISION CENTRAL DIVISION WESTERN DIVISION

B. IF NO, IN WHICH DIVISION DO THE MAJORITY OF THE PLAINTIFFS OR THE ONLY PARTIES, EXCLUDING GOVERNMENTAL AGENCIES, RESIDING IN MASSACHUSETTS RESIDE?

EASTERN DIVISION CENTRAL DIVISION WESTERN DIVISION

(PLEASE TYPE OR PRINT)

ATTORNEY'S NAME Edward J. Kelly

ADDRESS Ropes & Gray, LLP, One International Place, Boston, MA 02110

TELEPHONE NO. 617-951-7000

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